FULL-SCALE PERFORMANCE EVALUATION OF MOBILE ROOF SUPPORTS

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ABSTRACT

Two mobile roof supports (MRS's), one manufactured by J. H. Fletcher and Co. and one manufactured by Voest-Alpine Mining and Tunneling, were evaluated under controlled load conditions in the Strategic Structures Testing Laboratory at the Pittsburgh Research Center. A unique load frame, called the mine roof simulator, provided a realistic simulation of mining conditions by inducing vertical, horizontal, and lateral loading on the support. The purpose of these tests was to determine the performance capabilities and limitations of the supports and to investigate factors that influence the measurement of loading and loading rate. An evaluation of the support design and load conditions that can cause support failure or loss of support capacity is presented relative to the laboratory tests. In general, lateral loading perpendicular to the longitudinal axis of the canopy is most severe, although horizontal loading in the direction of the longitudinal axis of the canopy can also produce critical loading is some cases. The tests indicate that both setting force and leg pressure measurement are influenced by the staging of the leg cylinders. The implications of these factors on load rate measurement are evaluated. Differences in design philosophy between the two supports are identified and related to support performance. The difference in leg design, two- versus three-stage, had the most impact on support performance. Safety issues pertaining to support operation and maintenance are also discussed. Lastly, MRS capacity and stiffness characteristics are compared with those of conventional timber supports.

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INTRODUCTION

Mobile roof supports (MRS's) have improved the safety of pillar extraction during secondary mining by providing superior roof control and significantly reducing the materials handling associated with timber posts in pillaring operations. The superior capabilities of the MRS's have promoted pillar extractions in conditions such as weak roof and floor geologies prone to unpredictable caving that were previously too dangerous when using timber posts.

Since the introduction of MRS's in the United States in 1988, MRS technology has matured, with installations in more than 40 coal mines. Overall, MRS's have experienced widespread success. Few failures have been reported; these are typically attributed to lack of operating experience or severe conditions, such as those associated with the first or large areas of caving strata. Only one fatality has occurred on a mobile section; however, the fatality was not attributed to failure of the mobile supports. Nevertheless, some questions arose during the fatality investigation in 1995 regarding the performance capabilities of MRS's and the capability to assess ground instabilities from MRS loading.

In an effort to evaluate their support design, but unrelated to the fatality investigation, the two manufacturers of MRS's, J. H. Fletcher and Co., Huntington, WV, and Voest-Alpine Mining and Tunneling (VAMT), Pittsburgh, PA, made arrangements to have their supports tested at the Pittsburgh Research Center. One support from each manufacturer was evaluated at the Center's Strategic Structures Testing Laboratory through full-scale testing in the unique *mine roof simulator* load frame. Although the supports that were tested are similar in operating range and capacity, the Fletcher support utilized three-stage leg cylinders, whereas the VAMT support utilized two-stage leg cylinders. This difference in leg design should be considered when making comparisons of support performance, particularly the stiffness of the support.

A series of tests was conducted under controlled load conditions, which provides a better understanding of the performance capabilities and limitations of MRS's and factors that influence the measurement of loading and loading rate. This paper presents the results of these laboratory studies and compares differences in design philosophies and evaluates their impact on support performance. The supporting capabilities of MRS's is compared with those of conventional timber posts and cribs. Safety issues relative to support maintenance and operation are also discussed.

STRATEGIC STRUCTURES TESTING LABORATORY

The Strategic Structures Testing Laboratory is a unique laboratory where full-scale mining equipment and roof support structures can be tested in a controlled environment. Figure 1 shows an MRS in the laboratory's mine roof simulator load frame. This unique load frame is designed to simulate the loading induced on support structures due to the behavior of rock masses during mining. The load frame can provide controlled roof and floor movements to simulate the closure of the mine opening while generating up to 13,334 kN (3 million lb) of vertical force and 7,117 kN (1.6 million lb) of horizontal (shear) force.

The test procedure for the MRS evaluation was as follows:

1. The MRS was positioned in the proper orientation to allow the load frame to induce vertical, horizontal, or lateral loading on the support.
2. The MRS was actively set against the load frame platens using the internal hydraulic power to establish the initial load condition.
3. Subsequent loading was applied by controlled displacement of the load frame's lower platen to simulate closure of the mine entry. Three different load vectors were evaluated through applied vertical, horizontal, and lateral displacements, as depicted in figure 2.
4. The support response to the applied loading was measured through strain gauges and pressure transducers

Figure 1.—Full-scale testing of a mobile roof support in the unique mine roof simulator load frame.

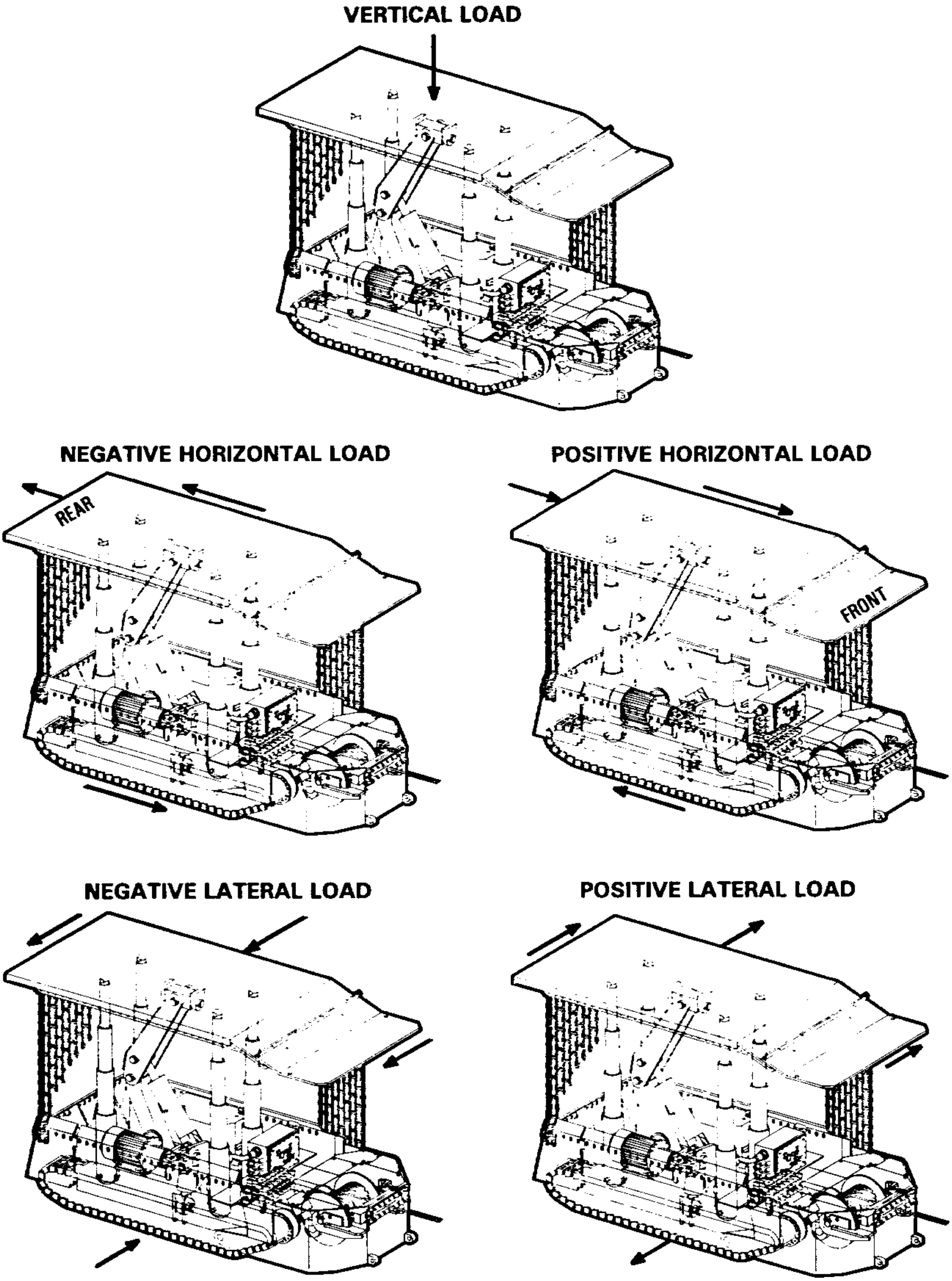


Figure 2.—Vertical, horizontal, and lateral loading applied to the mobile roof supports by the mine roof simulator.

installed on the various MRS components. A typical instrumentation arrangement is shown in figure 3.

Parameters investigated included (1) setting pressure, (2) support height, (3) load vector (direction of loading), and (4) canopy contact configuration. Additionally, a variety of eccentric crawler frame contact configurations were evaluated with the Fletcher support. The testing effort focused on the following studies:

1. *Rated support capacity:* Determination of maximum support capacity in relation to the support's rated design capacity.
2. *Stiffness characteristics:* Measurement of support resistance and component responses to roof movements in the vertical, horizontal, and lateral directions.
3. *Setting force:* Evaluation of setting force as a function of leg staging and hydraulic pump pressure.
4. *Load and load rate measurement:* Evaluation of factors that affect the measurement of roof load and loading rate.
5. *Conditions that reduce support capacity:* Identification of load conditions that reduce support capacity.
6. *Critical load conditions:* Identification of load conditions that maximize component loading and those that produce critical loading where the structural integrity of the supports could be jeopardized.

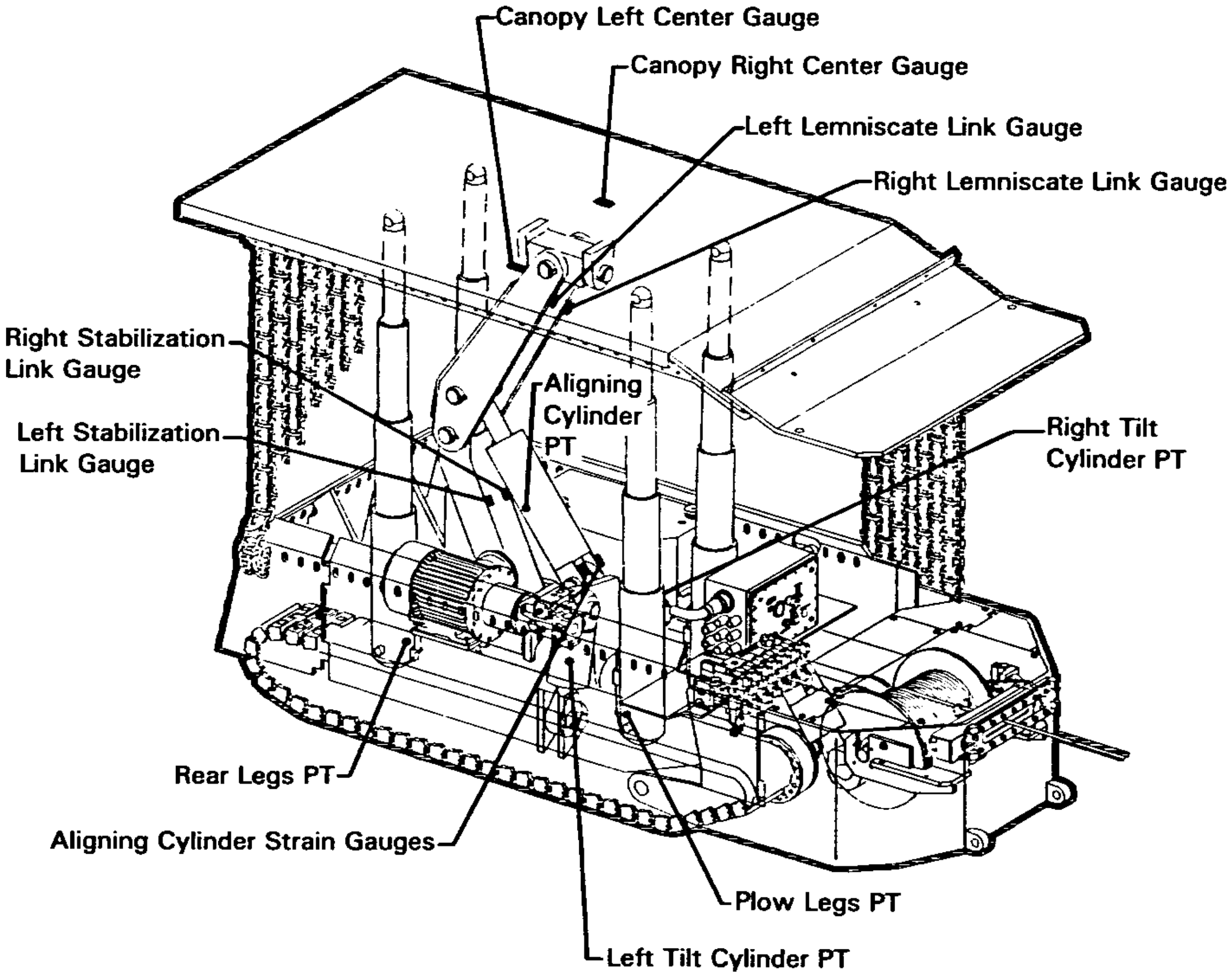


Figure 3.—Instrumentation installed on the VAMT support to assess support performance. PT = pressure transducer.

MOBILE ROOF SUPPORT DESCRIPTION AND BASIC DESIGN PHILOSOPHIES

The VAMT support tested during this study was a model 185/380-540. The Fletcher support was a model MRS-13 with 1.45 m (57 in) to 3.71 m (146 in) operating height. These support designs are representative of the support philosophies of the two manufacturers, although both manufacturers offer a variety of machines and designs to operate in mining heights ranging from 1.17 m (46 in) to 3.96 m (13 ft).

The similarities in support design for the two supports evaluated in this study are as follows:

- Both supports were rated at 5,338 kN (600 tons) of support capacity and designed to operate in high seams at heights up to 3.81 m (12.5 ft). The maximum capacity is controlled by hydraulic yielding of the leg cylinders.
- The canopy is connected to the base frame by four hydraulic leg cylinders and a lemniscate assembly. The hydraulic cylinders provide the (vertical) support capacity or resistance to roof-to-floor convergence. The lemniscate assembly acts to minimize horizontal canopy movement during raising and lowering of the support and provides resistance to horizontal and lateral loading.
- The connection of the lemniscate assembly to the canopy is articulated to permit pitch and roll rotations of the canopy independent of the lemniscate assembly to allow full contact in uneven roof and floor conditions.
- An internal hydraulic power supply provides active setting of the support against the mine roof and floor with independent control of the front and rear legs.
- Ground contact is established through the crawlers with the crawler frame designed to support the full 5,338 kN (600 tons) of roof load.

There are four significant differences in design philosophy between the two supports tested: (1) a flat-plate canopy construction versus a sloped-edge canopy construction, (2) a tilt-frame lemniscate assembly versus a rigid link lemniscate assembly, (3) internal versus exposed lemniscate assembly, and (4) a two- versus a three-stage leg cylinder design.

The Fletcher support utilized a canopy construction that is sloped at the edges, whereas the VAMT support utilized a flat-plate canopy design. The rationale for Fletcher's sloped-edge design is to accommodate edge and point loading with reduced deflection and stress at full load. The sloped edges are also intended to facilitate moving the support in uneven or jagged roof strata. A result of this design is increased canopy stiffness as the edge plates reduce the size and significantly stiffen the top canopy plate. The flexibility of the flat-plate canopy utilized in the VAMT support is illustrated in figure 4, where deflections as great as 7.6 cm (3 in) were observed over the length of the VAMT canopy when the support was loaded with a single contact placed near the canopy tip. The flat-plate concept typically provides greater roof coverage due to roof contact across the full width and length of the canopy structure. However, the greater roof contact will not necessarily translate into larger support loads, since the roof typically behaves as some sort of beam with support loading controlled by roof displacements and not the dead weight of the rock mass. The larger canopy can result in higher stress developments due to greater bending moments when the canopy is not uniformly loaded.

Another major design difference pertained to the lemniscate assembly. The VAMT support utilized a lemniscate assembly connected to a tilt frame that permits single degree-of-freedom rotation of the lemniscate assembly due to lateral loading (see figure 5). The rotation is controlled by hydraulic cylinders called tilt cylinders. This design minimizes stress development in the lemniscate assembly due to lateral loading, but allows lateral translation of the canopy once the yield pressure of the tilt cylinders is reached. The Fletcher MRS as tested did not incorporate a tilt frame for the lemniscate assembly and relies on the strength of the lemniscate structure and connecting joints to resist lateral loading. The consequence of this design is significantly larger stress development in the lemniscate assembly due to lateral loading; however, the lateral translation of the canopy as a function of applied load is less than that of the VAMT tilt-frame design, particularly when the yield pressure of the tilt cylinders is reached.

The VAMT support also utilized a hydraulic cylinder, called an aligning cylinder (see figure 6), for the top lemniscate link, versus a rigid steel link in the Fletcher support. The aligning cylinder limits horizontal load development, thereby minimizing stress development in the lemniscate assembly due to horizontal loading. When yield pressure is reached, the aligning cylinder yields through a 60-mm (2.4-in) stroke, permitting an equivalent horizontal displacement of the canopy relative to the base. When the rear legs are retracted, the aligning cylinder returns to its initial stroke and restores the canopy to its initial horizontal position.

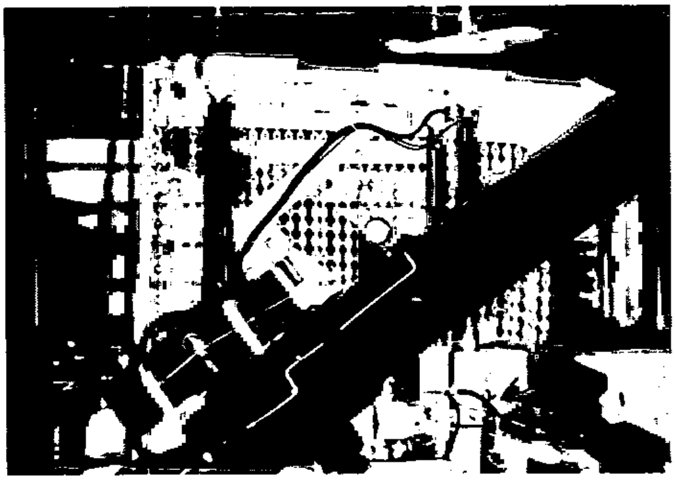
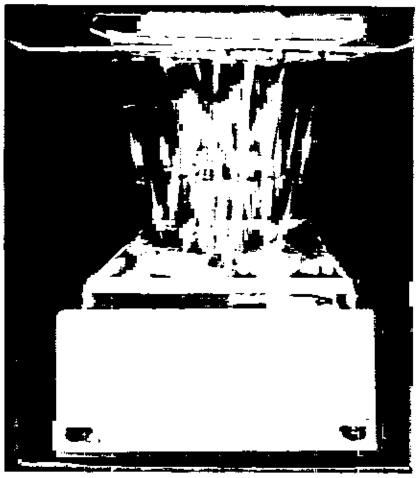


Figure 4.—Deflection of the VAMT canopy under partial contact loading.



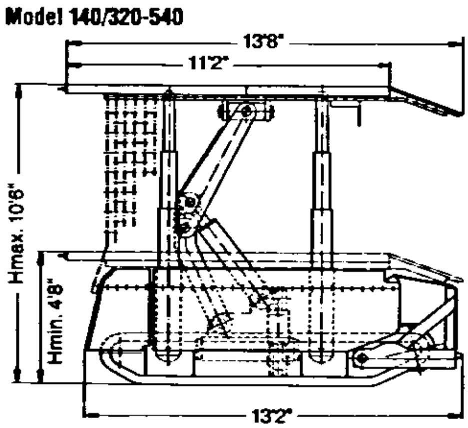


Figure 5.—Tilt-frame lemniscate assembly utilized on the VAMT support.

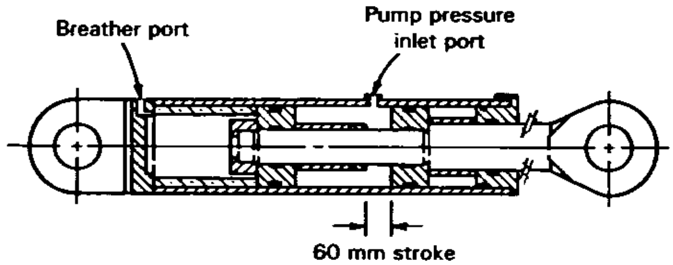


Figure 6.—Aligning cylinder designed to control horizontal loading on the VAMT support.

The position of the lemniscate assembly also differed for the two supports tested. The caving shield protruded beyond the rear of the canopy in the Fletcher support, whereas the entire lemniscate assembly was internal (within the confines of the canopy) on the VAMT support. The VAMT support utilized a chain curtain to resist gob flushing into the support. Fletcher contends that the external position of the caving shield provides increased protection to machine components from gob material and can act as a wedge to help to push the support from heavily caved areas. The exposed caving shield can also cause additional loading on the lemniscate assembly due to gob loading.

The Fletcher support that was tested utilized three-stage leg cylinders, as opposed to two-stage leg cylinders in the VAMT support. The rationale for the three-stage design is to enhance operating range. A consequence of the three-stage design is larger diameter leg cylinders, which impacts the operating pressure and several performance parameters, as described later in this paper.

ASSESSMENT OF LABORATORY TEST RESULTS

MAXIMUM SUPPORT CAPACITY

The maximum support capacity is controlled by hydraulic yielding of the leg cylinders, with a yield valve controlling the maximum pressure in the *bottom* stage of the leg cylinders. Normally, the left and right legs in the front and rear set are hydraulically connected together. As a result, the yield valve with the lowest operating pressure will control both legs in the set. The yield pressure required to provide a designated support capacity is a function of the effective area of the bottom stage of the leg cylinder. For example, the required yield pressure to produce 5,338 kN (600 tons) of support capacity was 26.3 MPa (3,820 psi) for the Fletcher support and 36.3 MPa (5,263 psi) for the VAMT support. This difference is due to the difference in leg diameters: 25.4 cm (10 in) for the Fletcher and 21.8 cm (8.6 in) for the VAMT support. The measured yield settings were approximately 38.4 MPa (5,575 psi) for the VAMT support, providing a maximum support capacity of 5,649 kN (635 tons), and 27.6 MPa (4,000 psi) for the Fletcher support, providing a maximum support capacity of 5,604 kN (630 tons).

STIFFNESS CHARACTERISTICS

Stiffness is a measure of how much roof movement is required to produce load resistance in the support. The stiffness characteristics of the support are evaluated for vertical, horizontal, and lateral displacements of the canopy relative to the base. Horizontal and lateral displacements are imposed in both a positive and negative direction (see figure 2). A comparison of the vertical, horizontal, and lateral stiffness at a 2.4-m (96-in) operating height is presented in table 1. As seen in the table, both supports are much stiffer vertically than horizontally or laterally; this means that much more roof movement is required to produce equivalent support resistance to the applied displacement in the horizontal or lateral direction than for roof-to-floor convergence. It should also be noted that the initial horizontal and lateral stiffness of the support is sensitive to translational freedom in the various joints of the lemniscate assembly and the gear train of the crawler drive assembly. The stiffnesses shown in table 1 represent the support response once this translational freedom has been removed.

Table 1.—Comparison of support stiffness at a 2.4-m (96-in) operating height

Load vector	Support stiffness, kN/cm (kips/in)[1]	
	VAMT support[2]	Fletcher support[3]
Vertical displacement	3,002 (1,714)	2,140 (1,222)
Horizontal displacement[4] ...	[5]271 (155); [6]137 (78)	315 (180)
Lateral displacement	[7]91 (52)	[8]137 (78); [9]39 (22)

[1]Stiffness measured when no leg stage is fully extended.
[2]Two-stage leg cylinder support design.
[3]Three-stage leg cylinder support design.
[4]Horizontal stiffness shown for horizontal displacement toward the plow of the support.
[5]Initial stiffness prior to pressure development in the aligning cylinder.
[6]Stiffness after aligning cylinder begins to develop pressure.
[7]Initial stiffness prior to yield of tilt cylinders. Load applications that would produce yielding of the tilt cylinders were not evaluated.
[8]Initial stiffness during first 1.3 cm (0.5 in) of lateral movement.
[9]Stiffness beyond initial 1.3 cm (0.5 in) of lateral movement.

Vertical Stiffness

Vertical stiffness is a measure of support resistance to roof-to-floor convergence. It is controlled almost entirely by the stiffness of the hydraulic leg cylinders. Vertical stiffness depends on the height of the support and decreases with increasing height (figures 7*A* and 7*B*). Therefore, the supporting force at a high operating height will be less than at a lower operating height for the same roof-to-floor convergence. Using the VAMT support as an example, the supporting force at a height of 3.8 m (148 in) is only 38% of the supporting force at a height of 2.4 m (96 in) for the same roof-to-floor convergence.

When none of the leg stages are fully extended, the support stiffness is constant from set to yield, and the setting pressure does not have a significant effect on the support stiffness. When the support is set with the bottom stage fully extended, the support capacity as a function of displacement is bilinear. The initial stiffness is high, since the effective column length is reduced to that of the upper stage of the leg cylinders, and decreases once the upper stage force exceeds that of the lower stage *setting* force. An example for the VAMT support with two-stage leg cylinders is shown in figure 8*A*, where the stiffness decreases at about 4,226 kN (950 kips) of loading, which is where the bottom stage is dislodged from its mechanical stop when set at 28.96 MPa (4,200 psi) setting pressure. Figure 8*B* shows an example of the change in stiffness for a Fletcher support with three-stage leg cylinders when both the bottom and middle stages were fully extended. The initial stiffness was reduced when the top stage force exceeded the setting force of 2,829 kN (636 kips) developed in the second stage.

As expected, the VAMT support was stiffer in response tovertical loading than the Fletcher support (see table 1). This is primarily due to the two-stage leg cylinder design in the VAMT support, compared with the three-stage leg cylinder design in the Fletcher support. All other things being equal, a three-stage leg cylinder will *always* be less stiff than a two-stage leg cylinder, because the stages act in series with the equivalent stiffness reduced as the number of stages increases, as shown in equation 1 for a three-stage leg cylinder. Equation 1 also indicates that the equivalent stiffness is never greater than the least stiff member. The stiffness of individual stages is governed primarily by the area and stroke of the cylinder, decreasing in stiffness as the area decreases or the stroke increases. Thus, the stage with the smallest diameter will be the least stiff stage and is likely to control the equivalent stiffness of the entire leg:

$$\frac{1}{K_E} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3}, \tag{1}$$

where K_E = equivalent stiffness of the leg cylinder,

K_1 = stiffness of stage 1,

K_2 = stiffness of stage 2,

and K_3 = stiffness of stage 3.

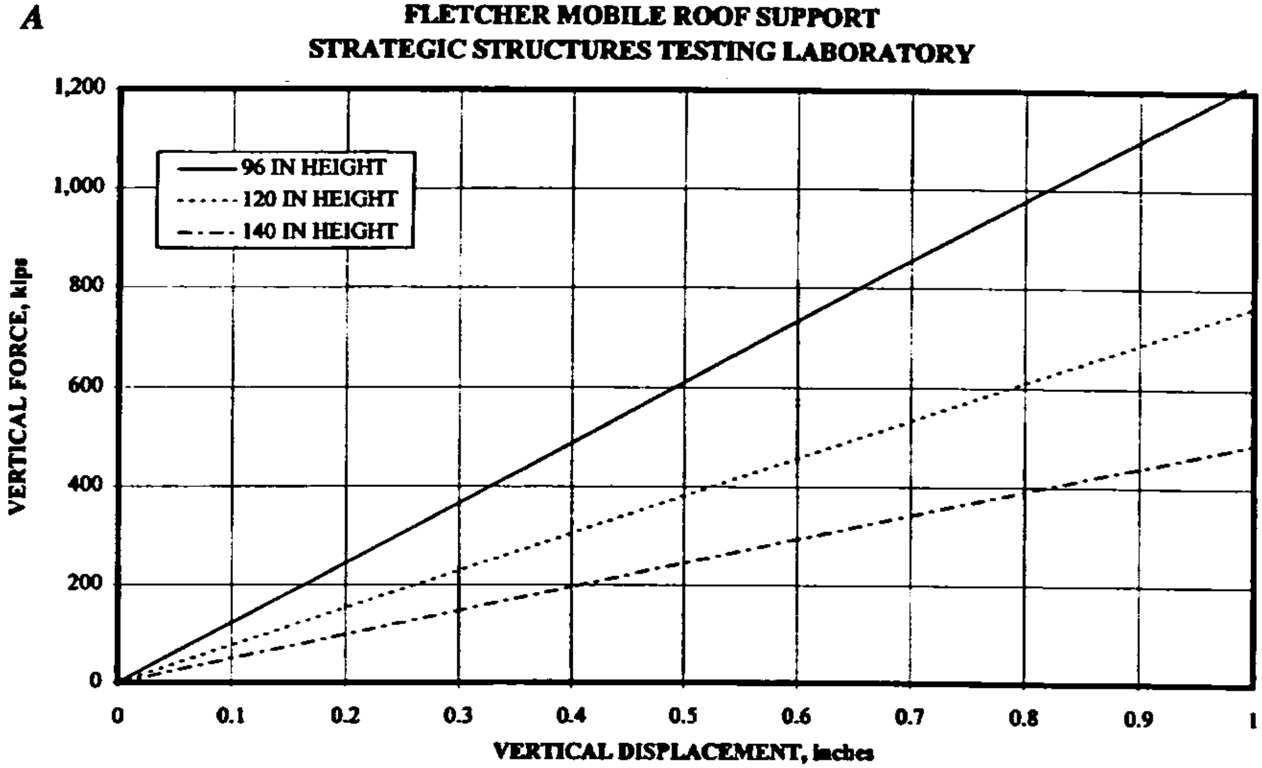
When both supports are set at the same leg *pressure*, they will reach yield load at nearly the same displacement. For example, with a setting pressure of 17.3 MPa (2,500 psi) at the 2.4-m (96-in) operating height, the VAMT support will reach yield load (5,338 kN (1,200 kips)) after 0.94 cm (0.37 in) of roof-to-floor convergence, compared with 0.86 cm (0.34 in) for the Fletcher support (see figure 9). However, when set to the same setting *force*, the Fletcher support will require 40% more displacement to reach yield load (see figure 10).

Horizontal Stiffness

Horizontal stiffness is a measure of support resistance to forward or rearward displacements of the canopy relative to the base. The action of the lemniscate assembly primarily controls the horizontal stiffness of MRS's, since the leg cylinders are nearly vertical and do not provide much resistance to horizontal loading. Horizontal stiffness is at least an order of magnitude less than the vertical support stiffness.

As previously indicated, the initial horizontal stiffness is controlled by translational freedom in the connecting joints of the lemniscate assembly and gear train of the drive motors. For example, up to 1.91 cm (0.75 in) of horizontal displacement of the canopy relative to the base was required in the VAMT support before any significant load resistance was generated. The horizontal stiffness of the support is also height-dependent, decreasing at increasing heights, as shown in the example in figure 11 for the Fletcher support.

A



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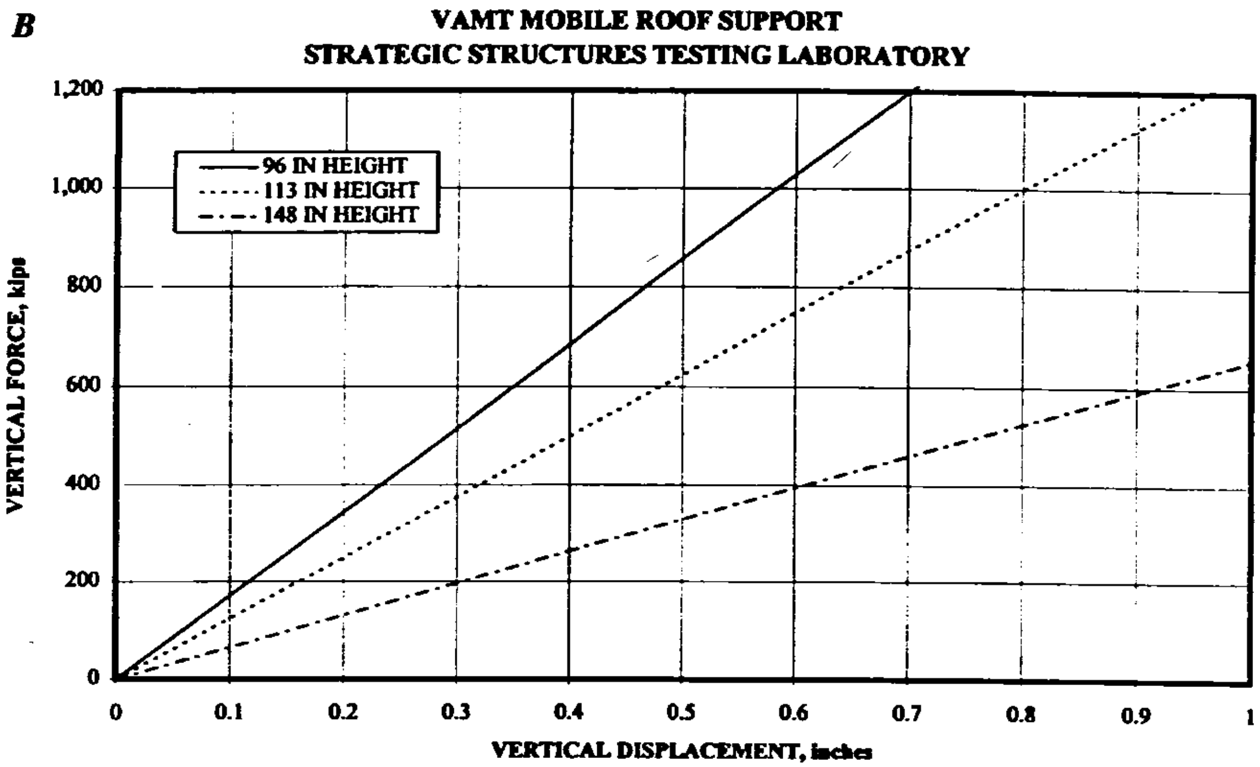
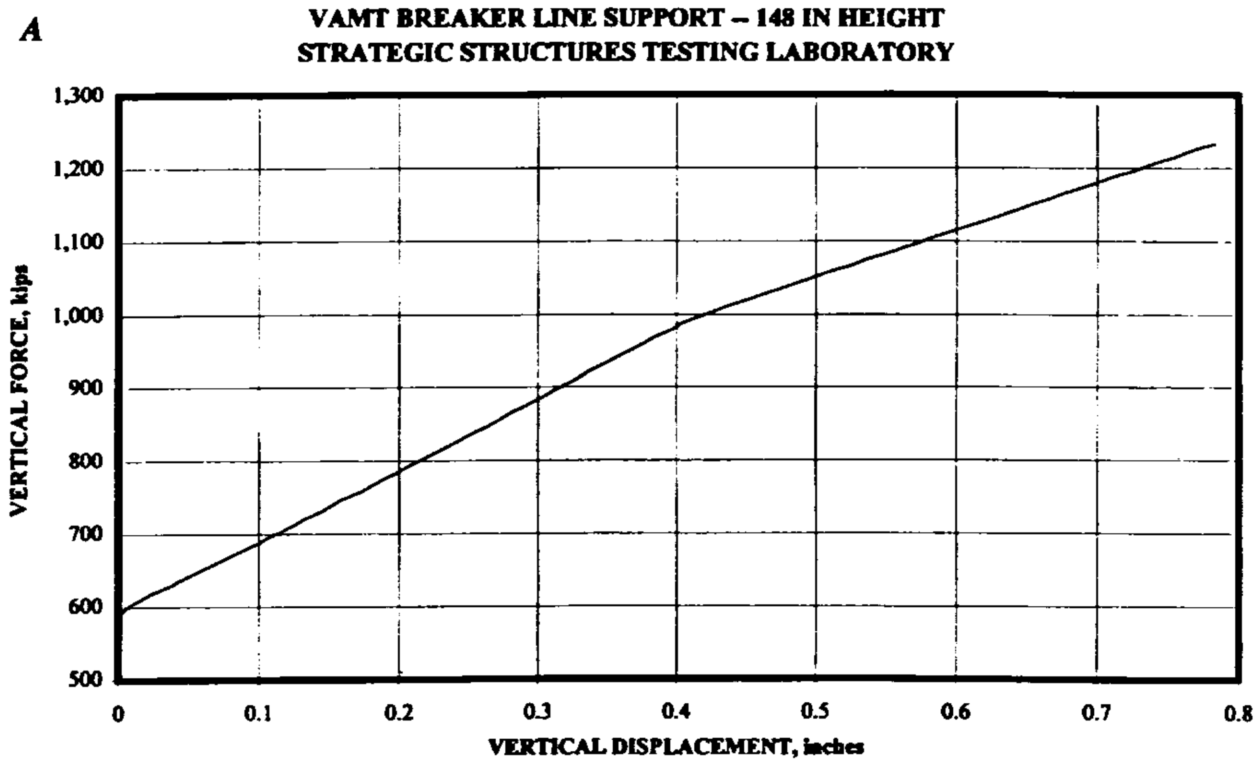


Figure 7.—Effect of support height on vertical stiffness. *A*, Fletcher support; *B*, VAMT support.

A



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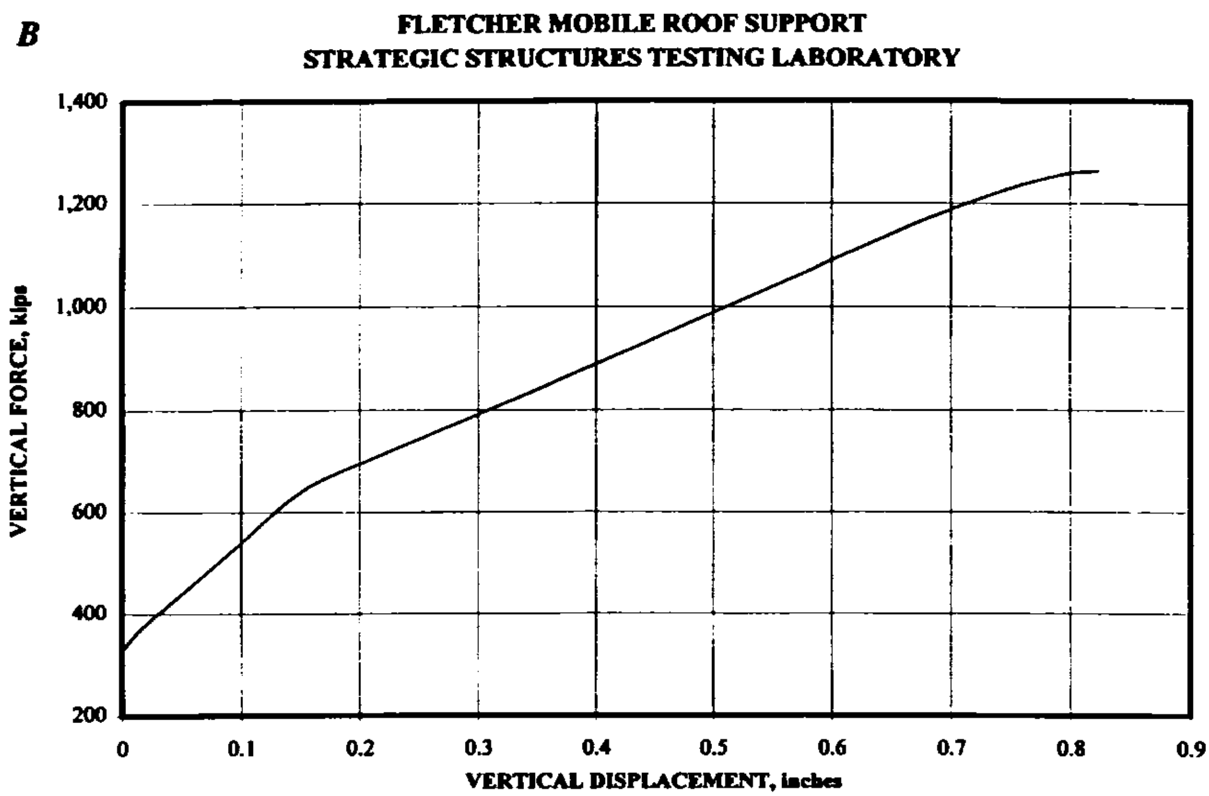


Figure 8.—*A*, Decrease in vertical stiffness on the VAMT support when bottom stage is fully extended at 0.4 in of displacement. *B*, Reduction in Fletcher support stiffness when both bottom and middle stages are fully extended at 0.15 in of displacement.

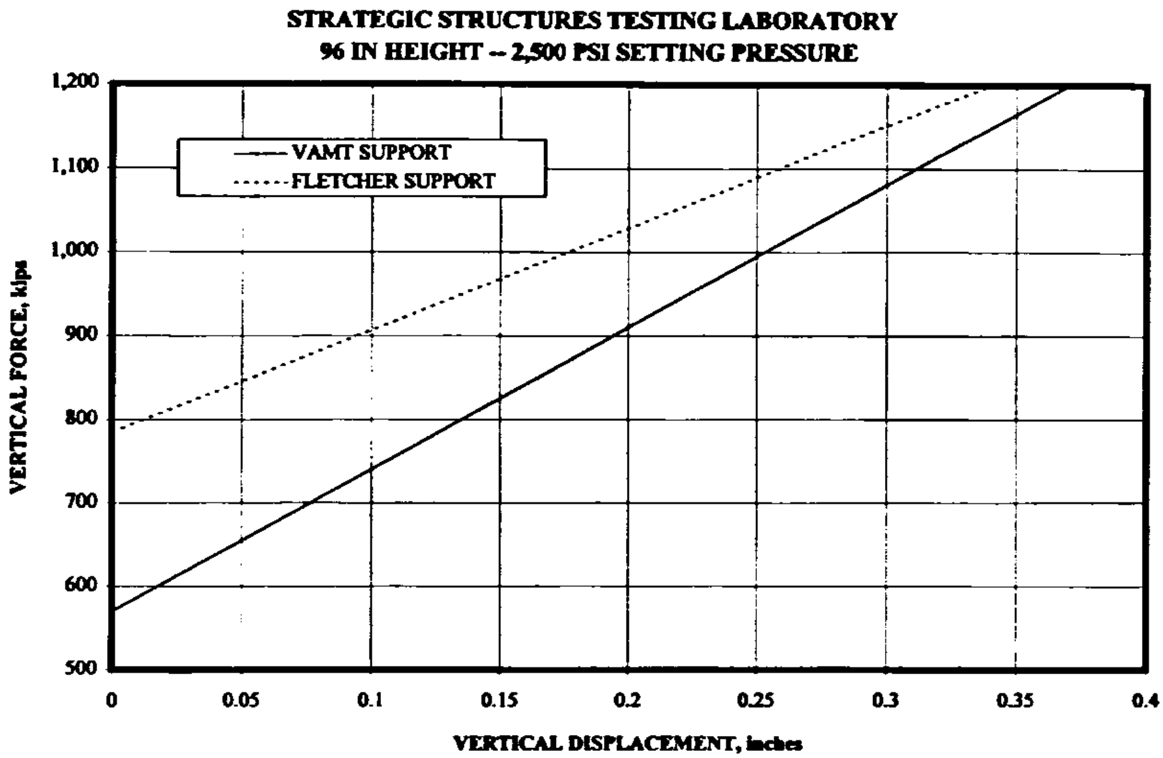


Figure 9.—Both the VAMT and Fletcher supports reach yield load at nearly the same displacement when set to the same leg pressure.

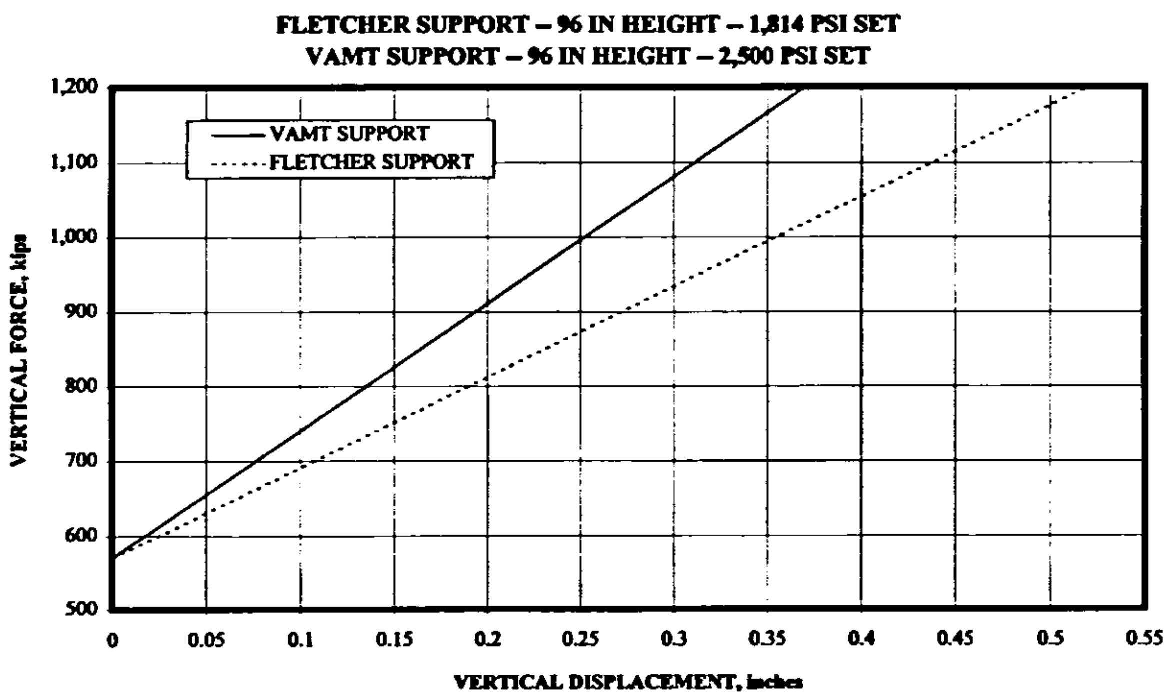


Figure 10.—Roof-to-floor convergence required to produce yield load in Fletcher and VAMT supports when both set to the same setting force.

Unlike the Fletcher support, which utilizes rigid lemniscate links, the horizontal force in the VAMT support, which utilizes a hydraulic aligning cylinder to limit the maximum horizontal loading, is a bilinear function of horizontal displacement. The horizontal stiffness at a particular height is reduced by as much as 50% when the aligning cylinder begins to develop load (see figure 12). For the example shown in figure 12 (horizontal displacement of the canopy toward the

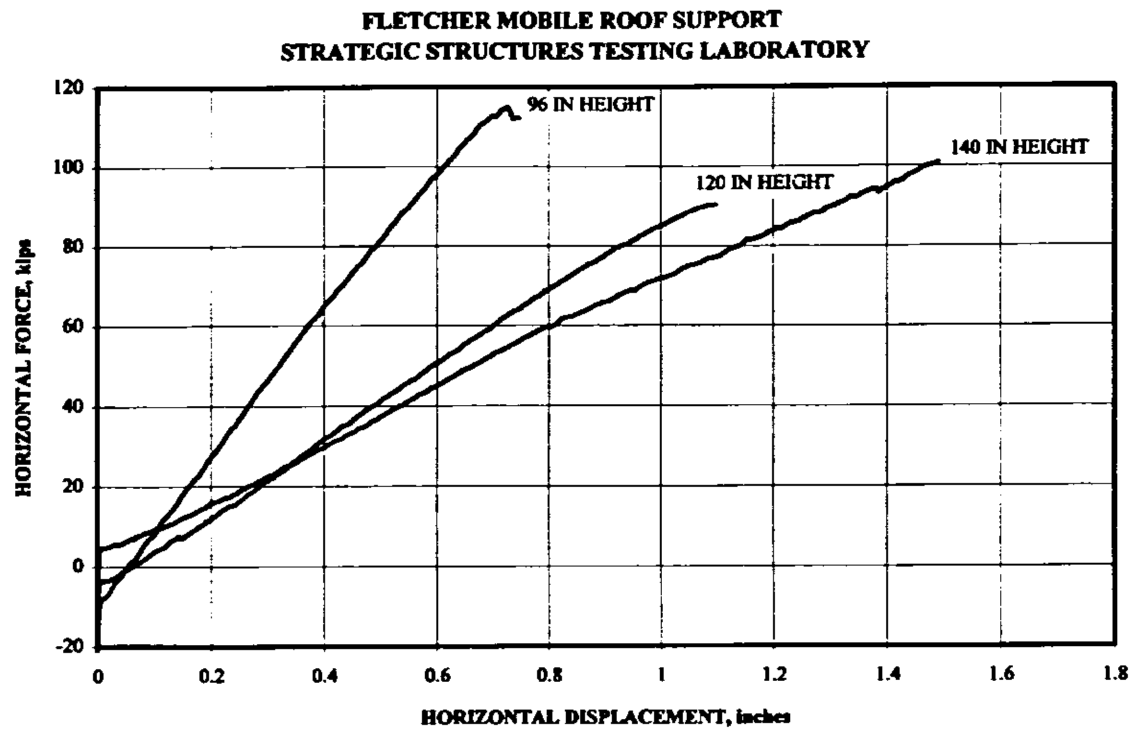


Figure 11.—Horizontal stiffness increases at decreasing support heights.

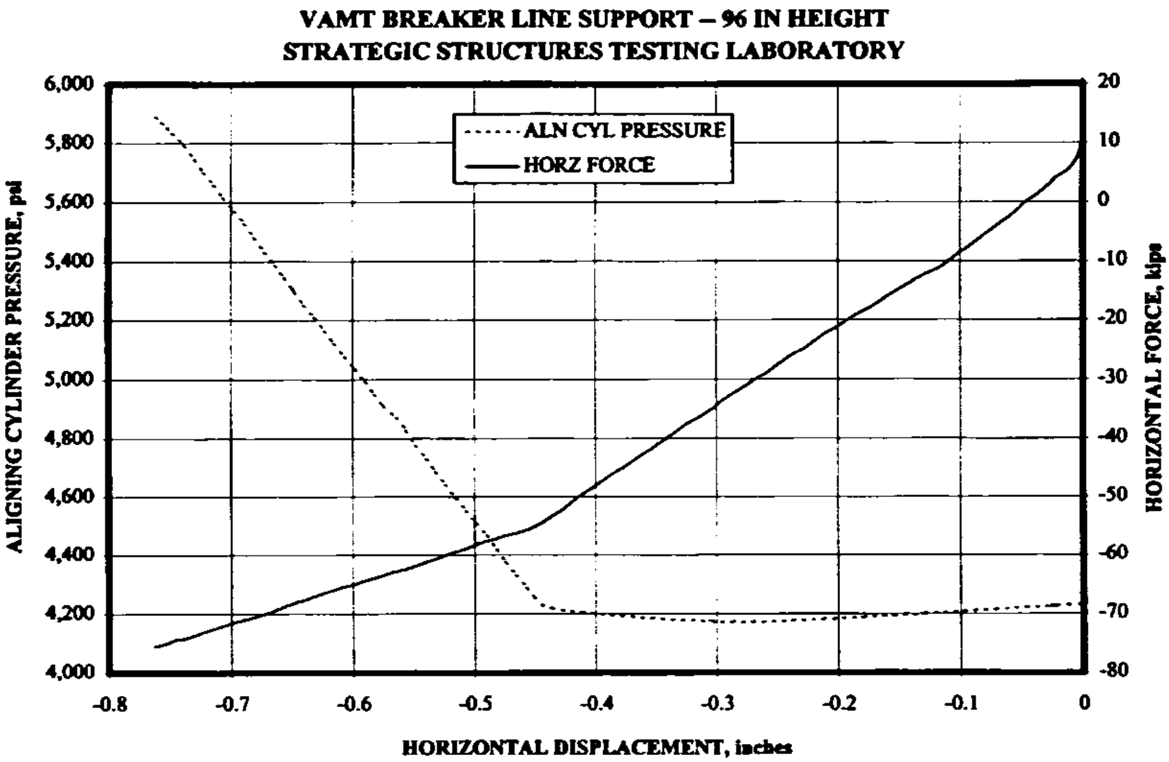


Figure 12.—Reduction in horizontal stiffness when pressure develops in the aligning cylinder.

caving shield), the initial horizontal stiffness is 233 kN/cm (133 kips/in), followed by a stiffness of 116 kN/cm (66 kips/in) after the aligning cylinder pressure began to increase. The horizontal stiffness of the Fletcher support is 2.3 times that of the VAMT support when the aligning cylinder is controlling horizontal load development.

Lateral Stiffness

Lateral stiffness is a measure of support resistance to applied left or right displacements of the canopy relative to the base. Thus, the direction of loading is across the width of the canopy versus along its length in horizontal stiffness evaluations. Lateral stiffness, as shown in figure 13, is also height-dependent.

For supports equipped with a tilt-frame lemniscate assembly such as the tested VAMT support, lateral stiffness is controlled primarily by the tilt cylinders, which control rotation of the lemniscate tilt assembly. The lateral stiffness of the Fletcher support tended to be bilinear with a high initial stiffness during the first 1.3 cm (0.5 in) of lateral movement, followed by a reduced stiffness for lateral movements beyond this, as shown in figure 14. The decrease in stiffness was greatest at the 2.4-m (96-in) operating height, with a 70% reduction in stiffness when the lateral movement exceeded 1.3 cm (0.5 in). The bilinear nature of the lateral stiffness is probably due to the interaction of the leg cylinders and the lemniscate assembly. This bilinear behavior was not observed in the VAMT support. As shown in table 1, the Fletcher support is stiffer than the VAMT support initially, whereas the VAMT support is stiffer than the Fletcher support when the lateral movement exceeds 1.3 cm (0.5 in).

The lateral stiffness is less than the horizontal stiffness by a factor of 3 for the VAMT support and a factor of 2.3 (initial stiffness) or a factor of 8 (final stiffness) for the Fletcher support at a 2.4-m (96-in) operating height.

ASSESSMENT OF SETTING FORCE

Setting force is defined as the force exerted against the mine roof and floor by actively setting the support using the internal hydraulic power. The setting force is determined by the effective leg area times the hydraulic pressure with the total setting force equal to the sum of all four leg cylinder forces. The effective leg area depends on the staging of the leg cylinders. Figure 15 compares the setting force as a function of hydraulic leg pressure with no stages fully extended for the Fletcher and VAMT supports. Because the VAMT support has smaller diameter leg cylinders—21.8 cm (8.6 in) compared with 25.4 cm (10 in) for the Fletcher support—greater pressures are required to produce equivalent setting forces. For example, approximately 17.4 MPa (2,530 psi) of pressure is required to produce 3,558 kN (800 kips) of setting force with the Fletcher support, whereas 24.1 MPa (3,500 psi) would be required to produce an equal setting force with the VAMT support.

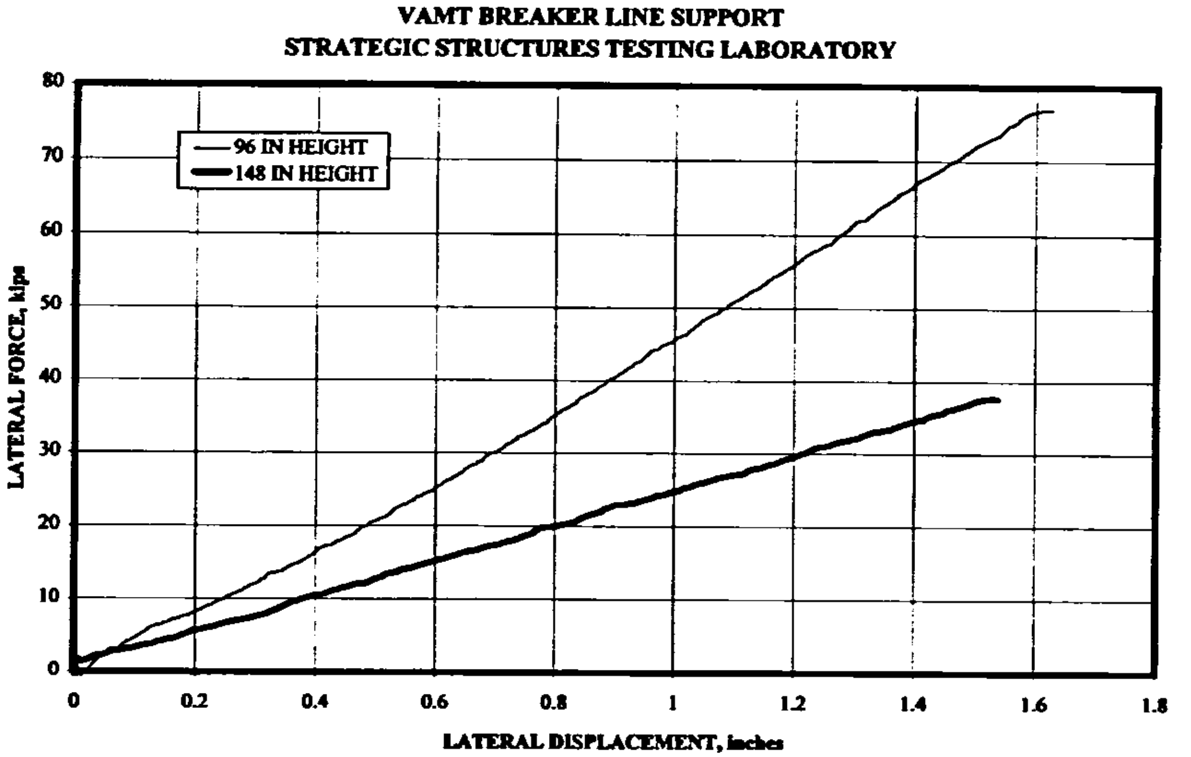


Figure 13.—Effect of height on lateral support stiffness. Left-to-right lateral displacement of the canopy.

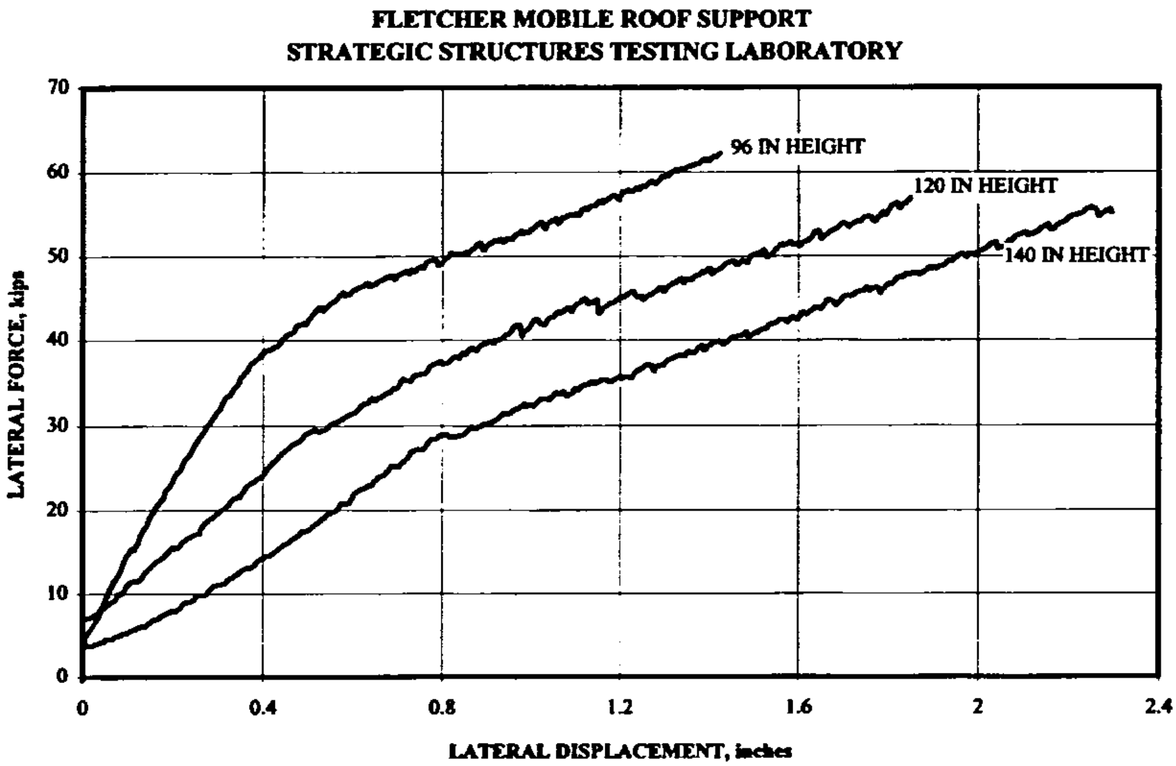


Figure 14.—Bilinear stiffness response to lateral loading.

The VAMT support utilized a two-stage leg cylinder, whereas the Fletcher support utilized a three-stage leg cylinder. Table 2 shows the reduction in setting force due to leg staging for the VAMT and Fletcher supports. As shown in the table, setting force can be reduced by as much as 70% for three-stage leg cylinders when the bottom and middle stages are fully extended. Because variances can also exist in each leg of the support with regard to staging, setting forces between the values shown in table 2 are possible. Thus, a wide range of setting forces can be provided for both supports even if the hydraulic setting pressures remain constant from set to set. An example of this is shown in figure 16.

Table 2.—Reductions in setting force due to leg staging

Leg stage condition	Reduction in setting force, %	
	Fletcher support [1]	VAMT support [2]
No stages fully extended	0	0
Bottom stage fully extended	45	42
Bottom and middle stage fully extended	70	NAp

NAp Not applicable.
[1]Three-stage leg cylinder design.
[2]Two-stage leg cylinder design.

The effect of leg staging on setting force development can be explained by examining the operation of the leg during setting and the associated leg mechanics, as depicted in figure 17 for a three-stage leg cylinder. Operationally, when the support is raised, the bottom stage is designed to extend to full extension first, followed by the middle and top stages. Likewise, when the support is lowered, the bottom stage retracts first, followed by the middle and top stages. The setting force will always equal the force developed in the stage with the largest diameter that is *not* fully extended, equaling the pump pressure times the area of that stage.

When the support is initially raised from a collapsed position to a height greater than the bottom leg extension, the setting force is diminished in proportion to the area reduction of the next stage, as depicted in table 2. On subsequent setting events, the setting force depends on whether full extension of leg stages is required due to changes in operating height. Once a support is extended to an operational height with a diminished setting force due to the bottom or middle stage being fully extended, the setting force will be restored to its maximum capability if the support is reset at *any* lower height, provided the bottom stage has not been fully retracted, and the setting force again will be diminished if the support is reset at an equal or greater height.

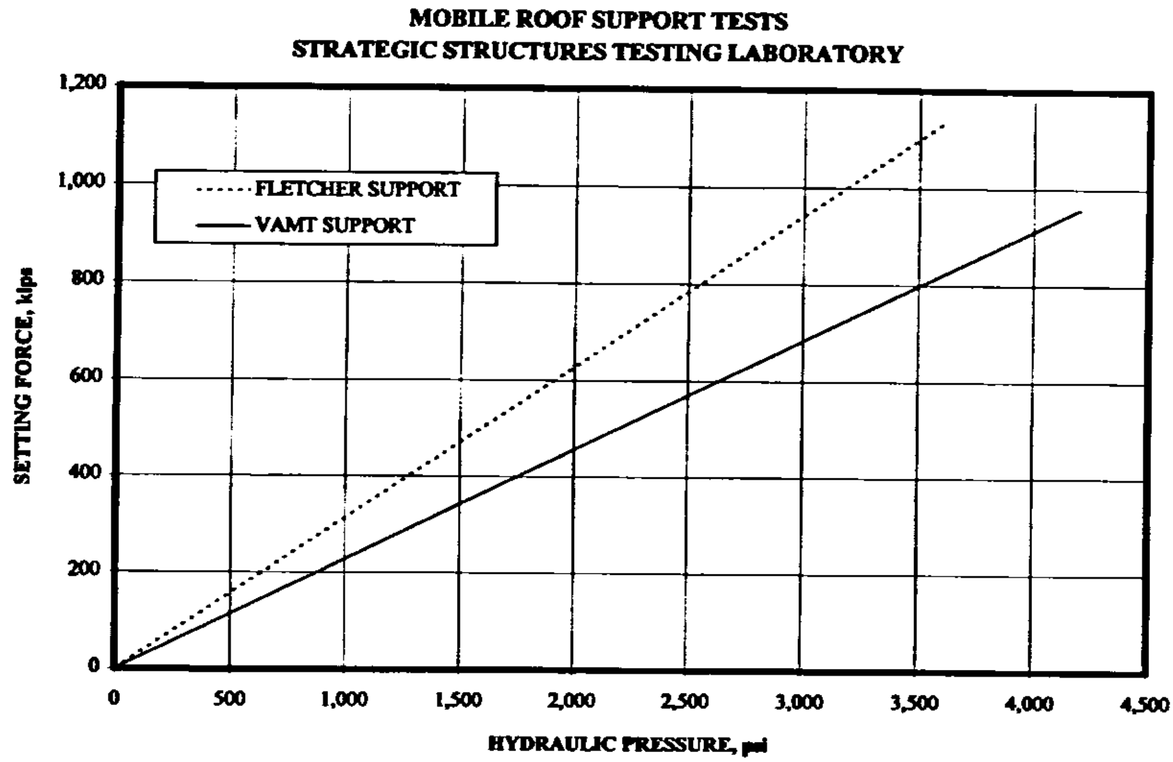


Figure 15.—Comparison of setting forces as a function of leg pressure with no stages fully extended for Fletcher and VAMT supports.

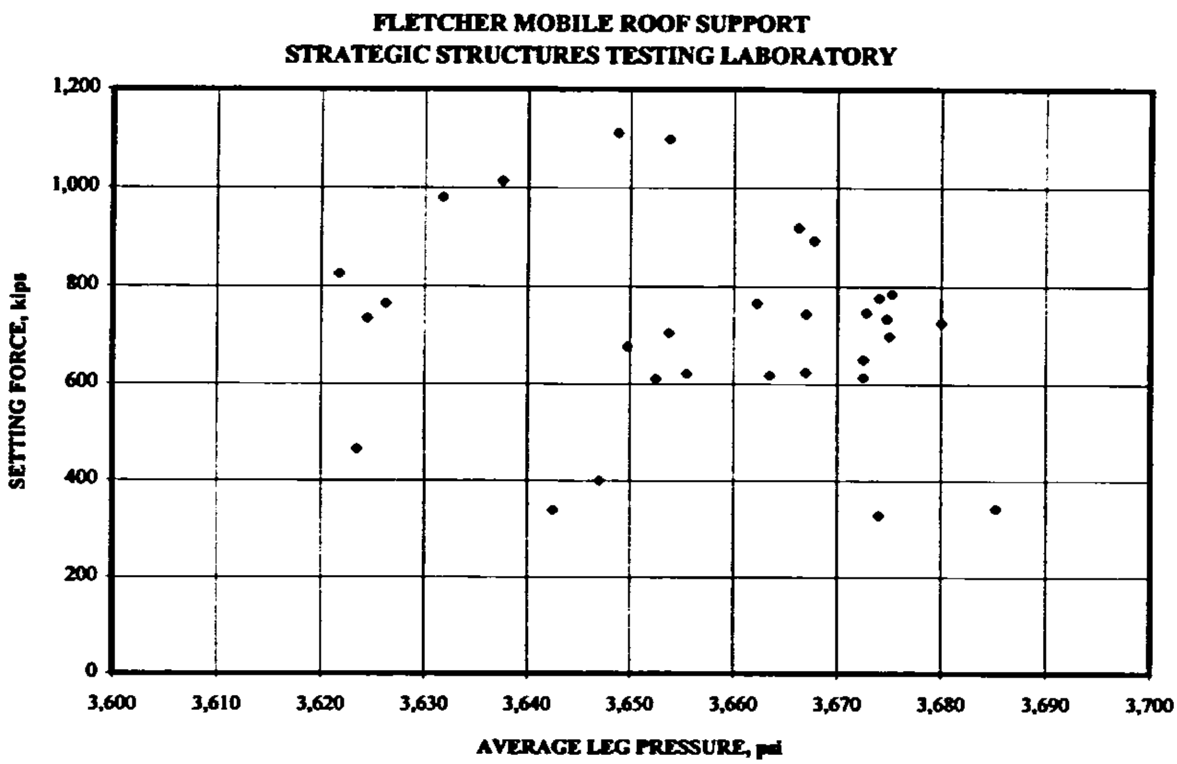


Figure 16.—Range of measured setting forces for maximum pump pressures.

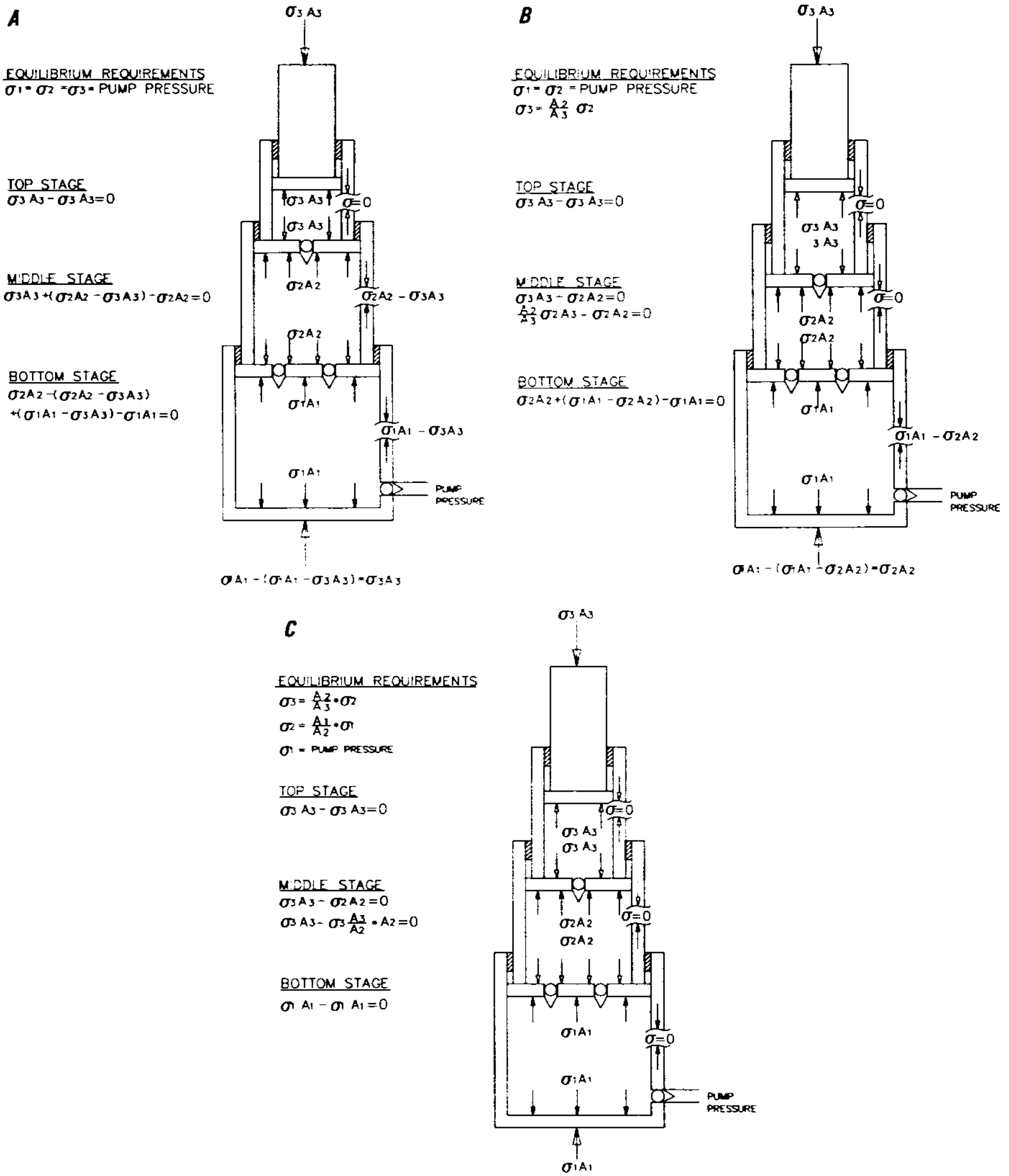


Figure 17.—Leg mechanics. ***A*, bottom and middle stages fully extended; *B*, bottom stage fully extended; *C*, no stage fully extended.**

An example is shown in figure 18 for a three-stage leg cylinder. Behavior of a two-stage leg cylinder can be deduced by elimination of the middle stage. Initially, the support is set at a height (H_{INT}) that causes the bottom stage to be fully extended, providing a diminished setting force. In preparation for the next cycle, the support is lowered, during which the bottom stage is partially retracted while the upper stages remain extended. When the support is reset (second cycle) at a lower operating height, full extension of the bottom stage is not required since the upper stages remain extended from the previous cycle. As a result, the setting force is restored to its maximum capability, equaling the setting pressure times the area of the bottom stage. Two scenarios are examined for the third cycle. In both cases, the support is reset at a higher operating height than the second cycle. In the first case, the support is raised to a height greater than the initial height. In this case, the bottom stage is fully extended once again and the setting force is once again diminished. However, if the support is raised to a height on the third cycle that is less than the initial height, full extension of the bottom stage is not required and full setting capacity is maintained.

In summary, during underground operation, the setting force will *always* be reduced on the mining cycle that establishes a *new maximum operating height* after an initial operating height that causes full extension of the bottom stage. All other cycles should provide full setting capability because extension of the bottom stage will not be required. Operationally, the probability of achieving maximum setting forces can be enhanced by establishing a maximum operating height as soon as possible. Ideally, when the support is initially taken underground, it can be brought to a location that is higher than where it will be placed into operation during pillar extraction, and fully extended. This will ensure full setting forces for all load cycles, provided the support is not lowered to the point where the bottom stage is fully collapsed, which would then cause retraction of the upper stages. In this case, a new maximum operating height would have to be established to prevent reductions in setting force.

FACTORS AFFECTING LOAD AND LOAD RATE MEASUREMENTS

Since the dial gauges on the support measure pressure in only the bottom stage of the leg cylinder, an assessment of load and loading rates can only be determined through the full load cycle when none of the stages are fully extended. If the bottom stage or bottom and middle stages (three-stage cylinder design) are fully extended, the dial gauges will not record changes in pressure until the setting forces in the extended stages are overcome by additional load development in the upper stages. When this condition occurs, roof loading during a beginning portion of the loading cycle will go undetected by the dial pressure gauges. The period of undetected roof loading depends on the setting pressure and will increase with increasing setting pressure in a particular support.

Using the VAMT support as an example, if the support is set with 29.0 MPa (4,200 psi) of hydraulic pressure with the bottom stage fully extended, a force of approximately 4,226 kN (950 kips) is generated in the bottom stage against the mechanical stops and 2,558 kN (575 kips) is generated in the upper stage acting on the mine roof. Because the bottom stage is fully extended, the dial gauges will remain inactive until the roof load acting on the support increases by 1,668 kN (375 kips) to cause the force in the upper stage to exceed 4,226 kN (950 kips) and cause the bottom stage to be moved off of its mechanical stops, resulting in an increase in pressure.

Figure 19 shows the magnitude of roof loading that is not recorded by the dial pressure gauges when one or more leg stages are fully extended as a function of the setting pressure. As seen in the figure, the unrecorded roof loads increase linearly with increasing setting pressure. As expected, the magnitude of unrecorded roof loading is much greater for the Fletcher three-stage leg cylinders than for VAMT two-stage leg cylinders because the bottom stage area is 35% larger in the Fletcher support, creating a higher setting force in the bottom stage compared with the VAMT support at the same hydraulic setting pressure. Additionally, when the bottom and middle stages are fully extended, the load difference between the top and bottom stages governs the unrecorded roof load. As shown in figure 19, unrecorded roof load ranged from approximately 445 kN (100 kips) at 6.9 MPa (1,000 psi) of setting pressure to as high as 1,690 kN (380 kips) at full pump pressure for the VAMT support and 609 kN (137 kips) at 6.9 MPa (1,000 psi) of setting pressure to 2,202 kN (495 kips) at full pump pressure when the bottom stage of the Fletcher support is fully extended. When both the bottom and middle stages are fully extended, 3,509 kN (789 kips) of roof loading can go undetected by the dial gauges when the Fletcher support is set to full pump pressure.

Therefore, a false sense of loading and loading rate can be interpreted from the pressure gauges when the bottom leg stage is fully extended. This can result in unreliable information for operators that utilize support loading to assess roof stability and impending roof caving. Full extension of the bottom stage can occur at heights greater than 50% of the operating range for a two-stage leg cylinder and at heights greater than 33% of the operating range for a three-stage leg cylinder (assuming equal stroke of the leg stages). However, the inaccurate information occurs only when a new maximum operating height is attained; therefore, the probability of inaccurate information depends on the mining conditions.

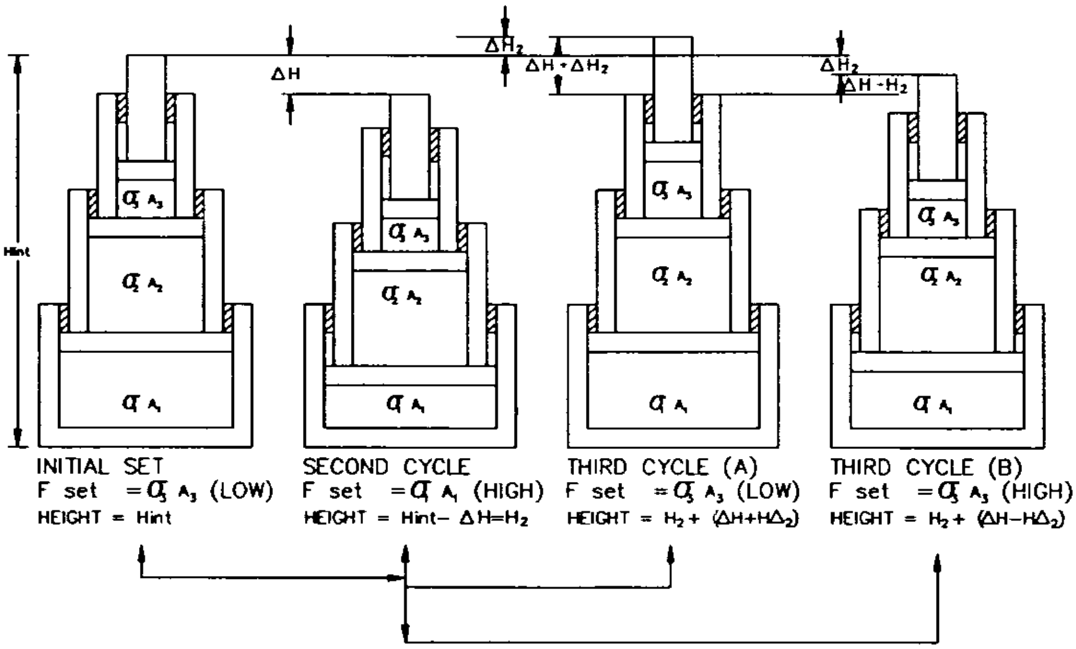


Figure 18.—Conditions that produce diminished setting force and unrecorded roof loads.

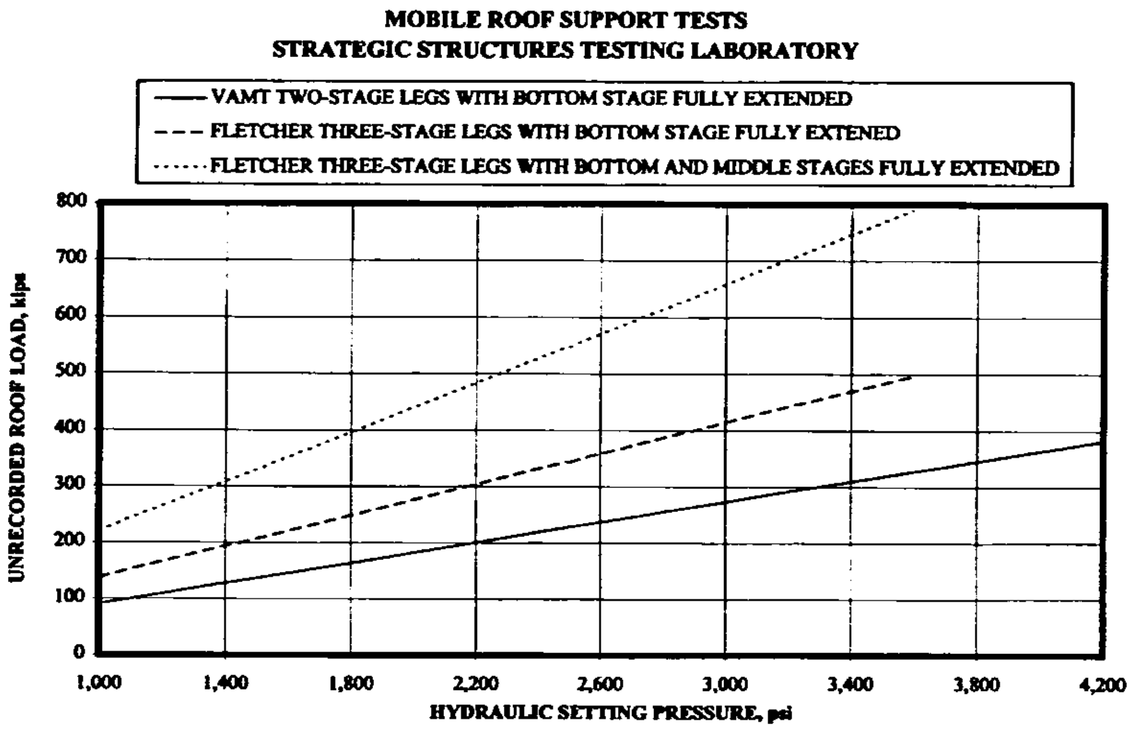


Figure 19.—Unmeasured roof load when one or more of the stages are fully extended as a function of setting pressure in the leg cylinders.

CONDITIONS THAT REDUCE SUPPORT CAPACITY

One cause of reduced support capacity is the bleed-off of hydraulic pressure from the leg cylinders under static loading conditions. Bleed-off rates of 69 kPa (10 psi) to 138 kPa (20 psi) per minute were common to both supports tested. As shown in figure 20, approximately 356 kN (80 kips) of load resistance was lost in 30 min because of loss of leg pressure under static loading for the VAMT support.

Horizontal loading can either increase or decrease support capacity depending on the change in leg pressures between the front and rear set of legs and the reaction of lemniscate assembly. Leg cylinders that are inclined toward the direction of the horizontal displacement will generally increase in pressure; those inclined away from the direction of the horizontal displacement will generally lose pressure. The net pressure change between the front and rear set of legs will generally determine whether the support capacity will be reduced or increased. However, the reaction of the lemniscate assembly must also be considered. For horizontal displacement of the roof acting to push the canopy toward the caving shield, the lemniscate assembly develops an upward reaction at the canopy connection, which increases support capacity. Likewise, when the horizontal displacement is toward the plow, a downward reaction is developed at the canopy connection, which reduces support capacity.

For the two supports tested, horizontal displacement produced the most change in support capacity at the lower heights because of the greater leg inclination. Figure 21 depicts the effect of horizontal loading on support capacity for the VAMT and Fletcher supports at a 2.4-m (96-in) operating height. As shown in the figure, support capacity was reduced for horizontal roof displacement toward the caving shield end of the canopy, and support capacity was increased when the horizontal canopy displacement was toward the plow. A maximum reduction in support capacity of 334 kN (75 kips) was observed for the VAMT support as a result of 2.0 cm (0.78 in) of horizontal roof displacement toward the rear of the canopy. Figure 22 is an example of an *increase* in VAMT support capacity despite a *reduction* in leg pressures on both the front and rear set due to the reaction of the lemniscate assembly.

Lateral displacements of the canopy in both directions tended to produce a loss of leg pressure that resulted in loss of support capacity. An example is shown in figure 23 for the Fletcher support. Support capacity was reduced by 378 kN (85 kips) on the VAMT support for left-to-right lateral displacement of the canopy at a 2.4-m (96-in) operating height with no significant loss of leg pressure (see figure 24), which suggests a negative reaction by the lemniscate assembly.

Figure 25 compares the effects of horizontal and lateral loading on support capacity at a 2.4-m (96-in) operating height for the Fletcher and VAMT supports. As shown in the figure, reductions in support capacity were greater for horizontal loading than lateral loading for both supports.

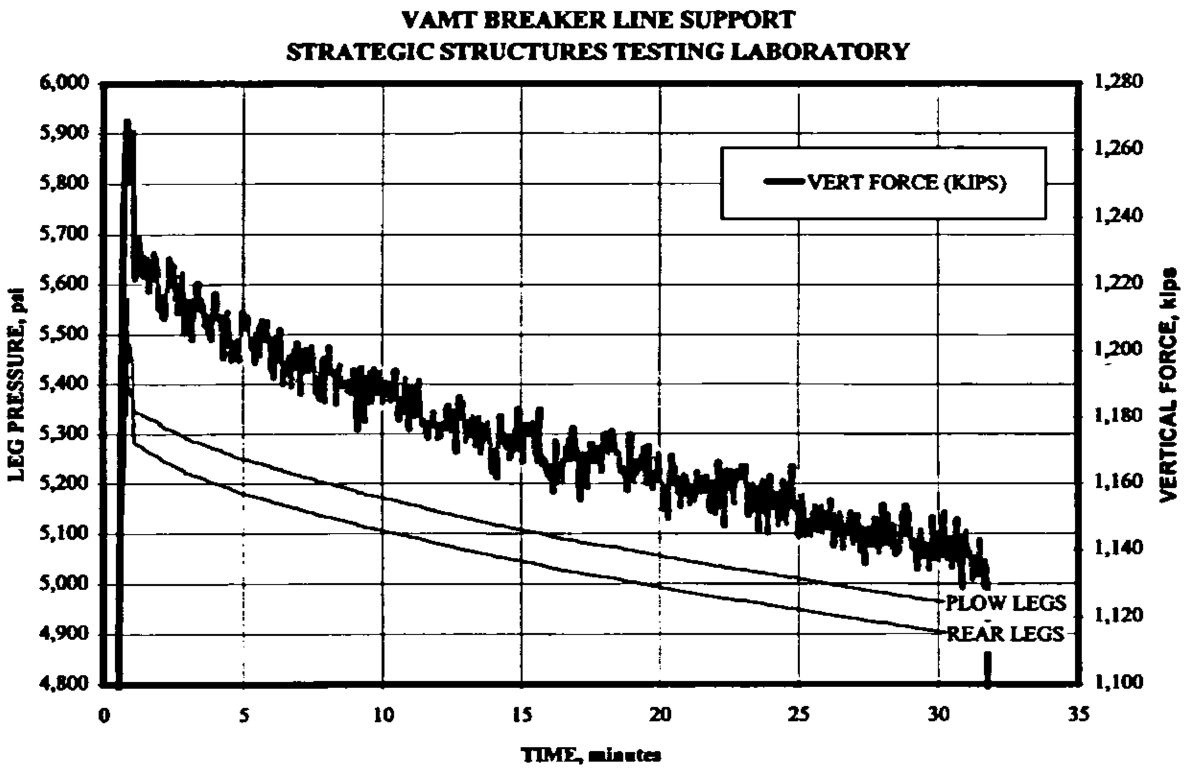


Figure 20.—Reduction in support capacity due to bleed-off of leg pressures after leg yielding.

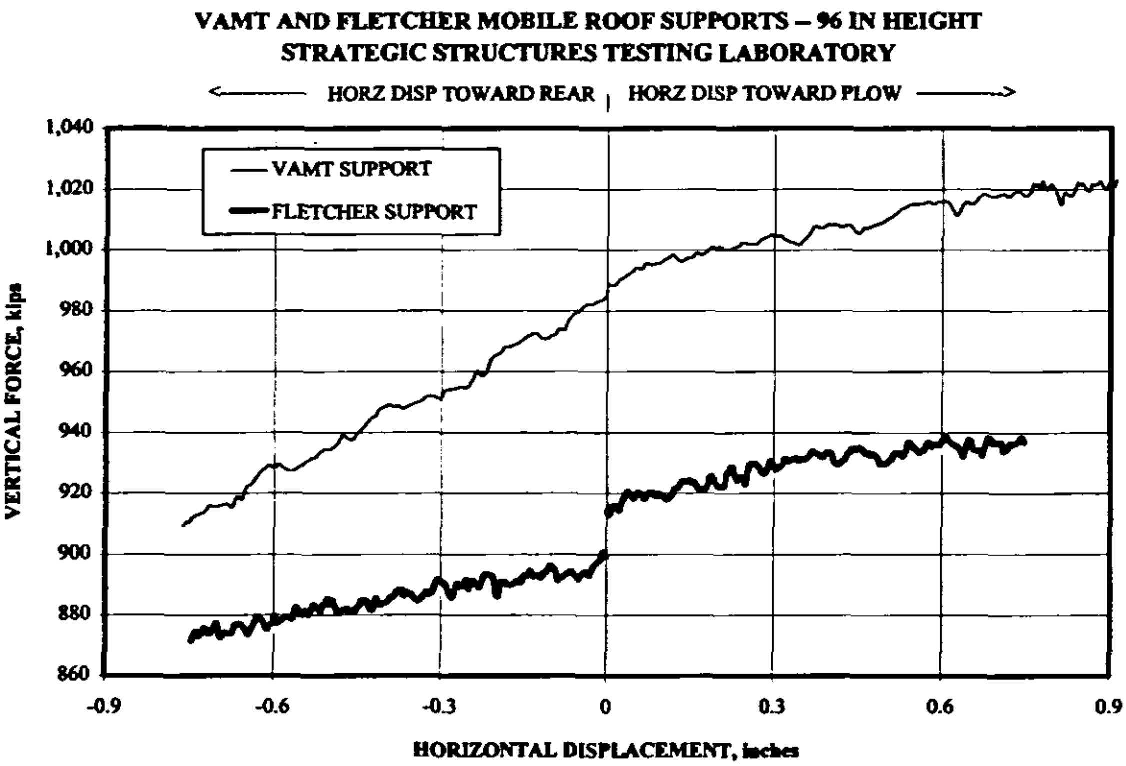


Figure 21.—Increase in support capacity for horizontal displacement toward the plow and decrease in support capacity for horizontal displacements toward the rear.

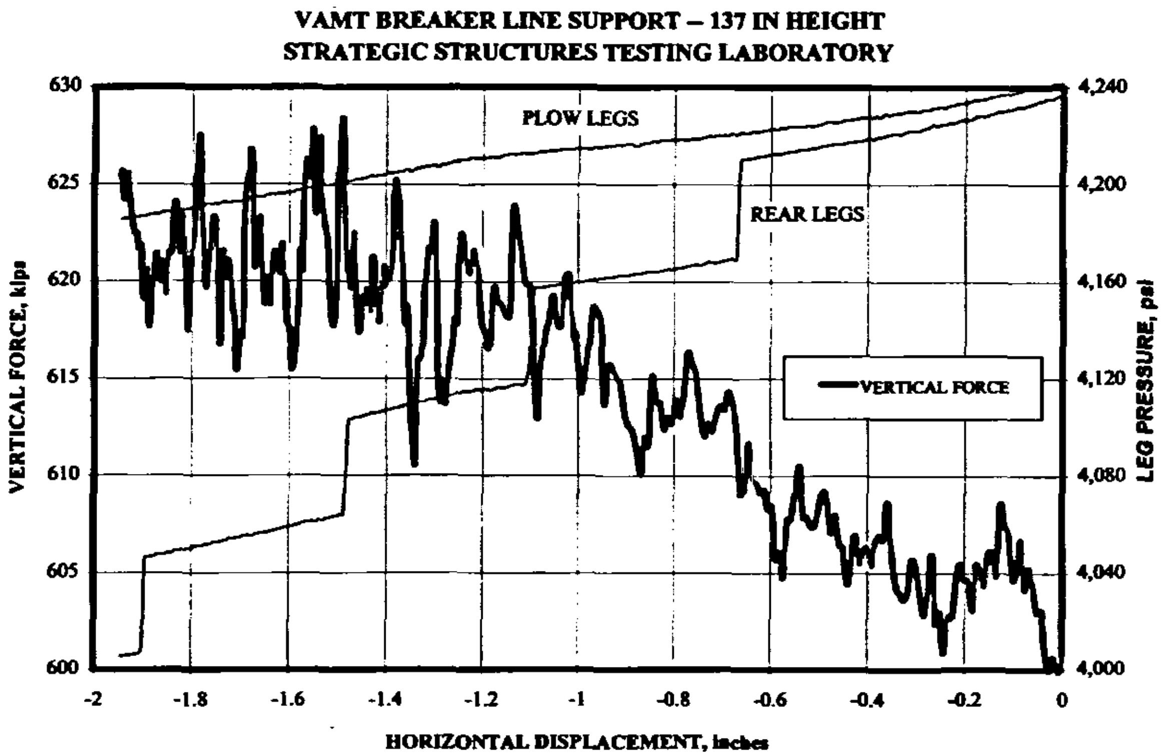


Figure 22.—Increase in support capacity despite a reduction in leg pressures.

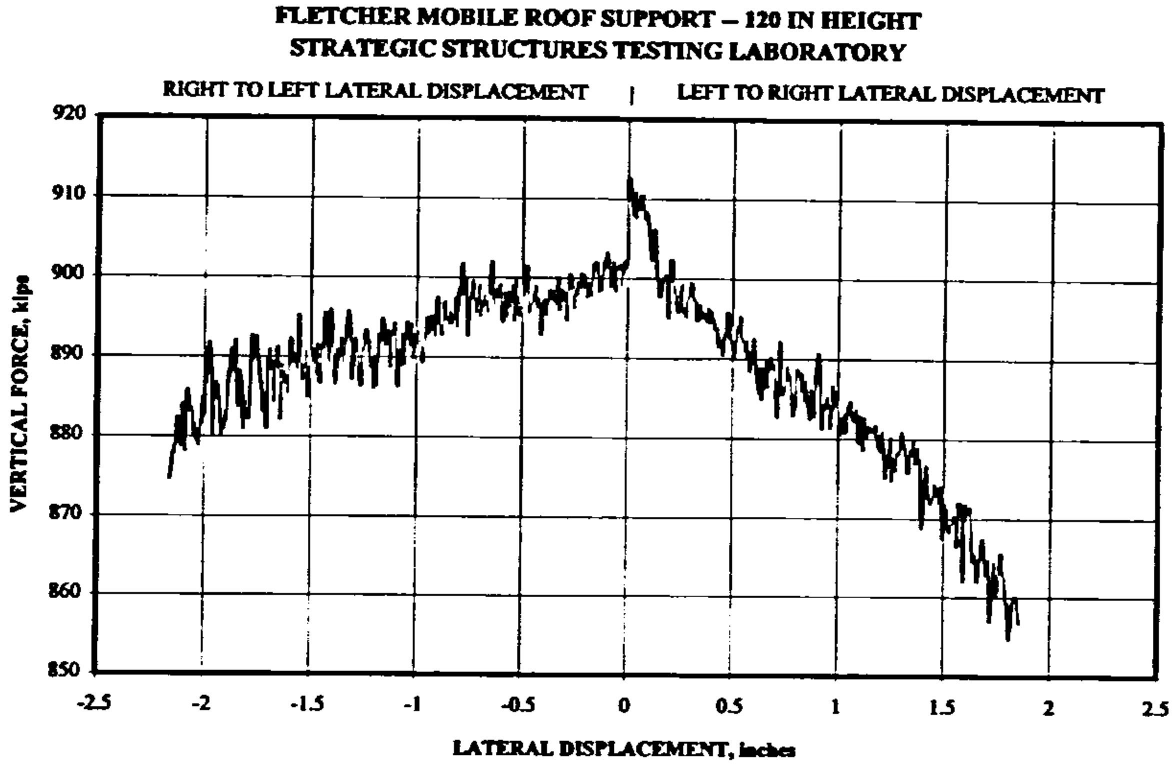


Figure 23.—Reduction in support capacity as a function of direction of lateral loading.

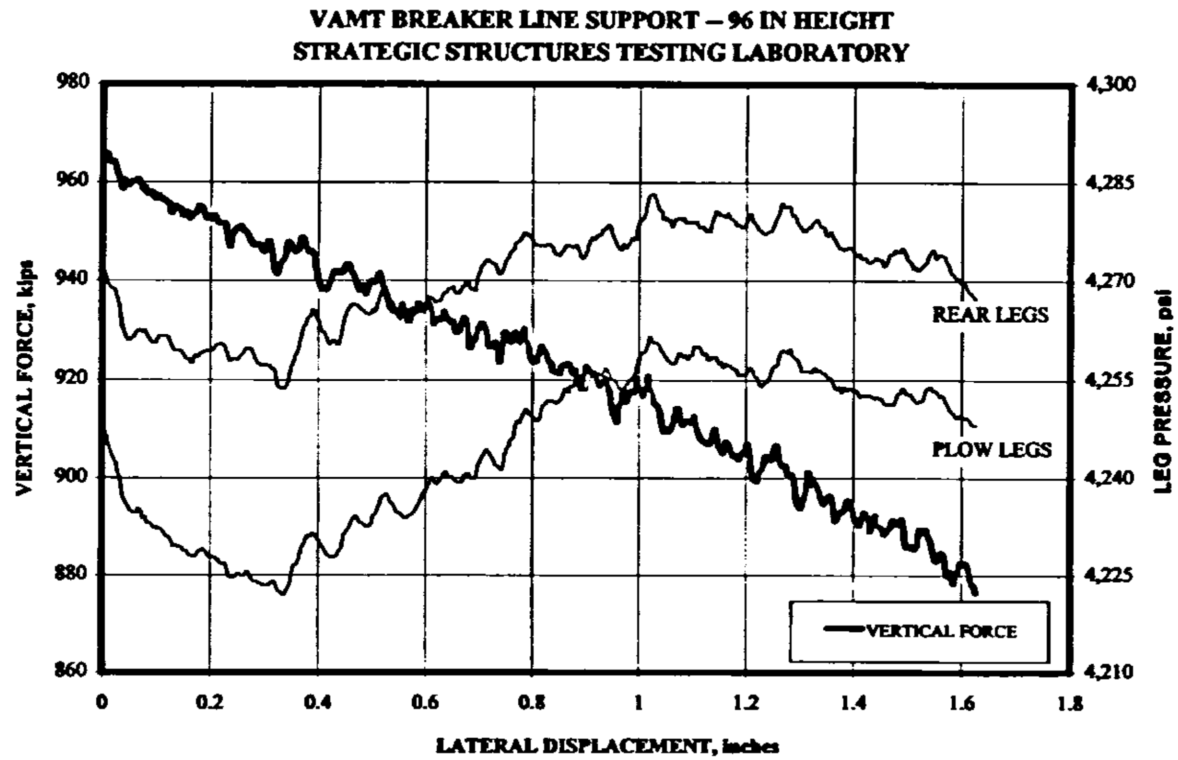
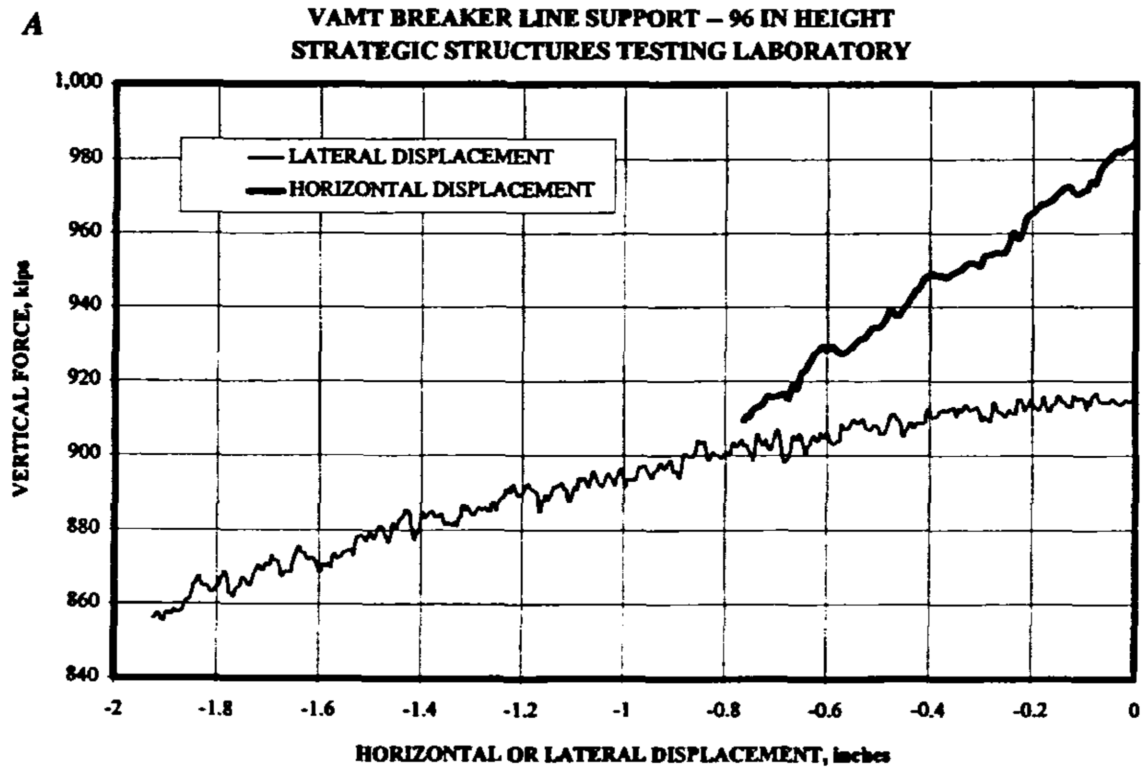


Figure 24.—Reduction in support capacity due to lateral loading with no significant loss of leg pressure.



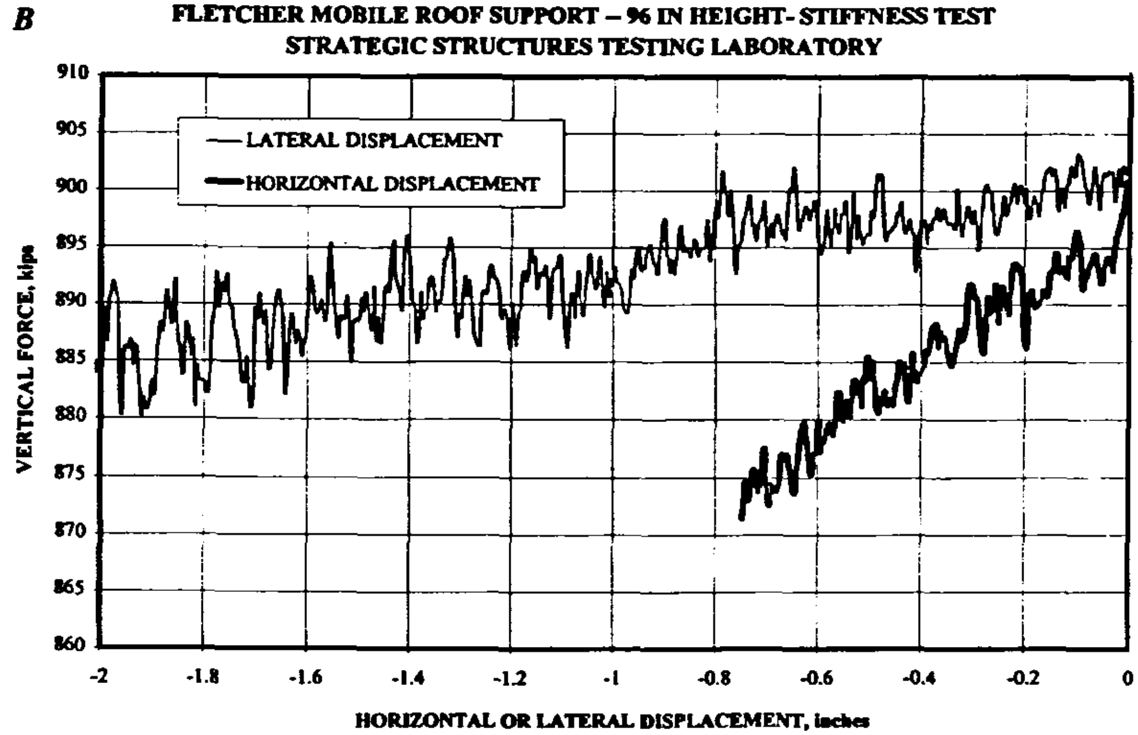


Figure 25.—Comparison of the effects of horizontal and lateral loading on reductions in support capacity. *A*, VAMT support; *B*, Fletcher support.

CRITICAL LOAD CONDITIONS

In general, the worst-case load condition for MRS's is lateral loading that causes lateral displacement of the canopy relative to the crawler frame. All of the rotational joints within the support structure are designed with a single rotational degree of freedom. Because lateral loading produces rotations along axes perpendicular to this rotational degree of freedom, it is the most severe load condition.

Depending on the stiffness of the lemniscate assembly, horizontal loading can also produce critical loads in the lemniscate assembly components. VAMT uses a hydraulic cylinder in lieu of a rigid lemniscate link to limit stress development in the lemniscate assembly due to horizontal loading.

The worst-case load conditions for canopy and base structures are partial contact configurations that induce bending. The associated stress development will be a function of the stiffness of the structure in relation to the applied loading.

STRUCTURAL INTEGRITY OF THE VAMT AND FLETCHER SUPORTS

Obviously, the effects of the above critical load conditions will be specific to a particular support design. A summary evaluation of the structural integrity of the VAMT and Fletcher supports based on measured component strains follows. However, it should be noted that the strain gauges were intended to assess load transfer through the various support components and were not necessarily positioned to measure maximum loading in any one component. All components were evaluated on both supports, except the crawler frame on the VAMT support.

VAMT Support

Highly loaded components on the VAMT support were the aligning cylinder and the canopy.

The amount of horizontal force acting on the support required to produce pressure development in the aligning cylinder varied from 178 to 467 kN (40 to 105 kips) for support heights ranging from 2.4 to 3.8 m (96 to 148 in). Once pressure development begins, only another 67 to 89 kN (15 to 20 kips) is required to produce a yield pressure of 40 MPa (5,800 psi) in the aligning cylinder. An example is shown in figure 26. In this case, 245 kN (55 kips) of horizontal loading acting to displace the canopy toward the rear of the support was required to produce pressure development in the aligning cylinder, and approximately 89 kN (20 kips) of additional horizontal loading produced a pressure of 40 MPa (5,800 psi). In this example, the displacement required to initiate pressure development in the aligning cylinder was 1.14 cm (0.45 in), with 0.76 cm (0.3 in) of additional displacement required to produce a maximum pressure of 40 MPa (5,800 psi) in the aligning cylinder (see figure 27).

A malfunction of the aligning cylinder occurred during a test in which the cylinder was yielded in compression under the application of horizontal displacement of the canopy toward the plow. At the completion of the test when the pump pressure was applied to the cylinder during the retraction of the rear legs, hydraulic fluid under considerable p ure blew out of the breather port on the base of the cylinder, indicating that the lower piston seals had been damaged. Strain data were recorded during the test from two strain gauges located on the clevis that connects the cylinder to the tilt-frame assembly. The strain responses are displayed in figure 28. An examination of the strain data suggests that the damage occurred at approximately 13 cm (5.1 in) of horizontal displacement of the canopy relative to the base. The sharp increase in strain that occurred just prior to this suggests that the cylinder was fully stroked. However, an analysis of the lemniscate geometry indicates that approximately 23 cm (9 in) of horizontal canopy movement is required to compress the aligning cylinder through its full 60 mm (2.4 in) of stroke. An examination of the damaged cylinder by VAMT revealed that the cylinder was radially deformed (ballooned), suggesting that the failure was caused by excessive hydraulic pressure. However, the strain data indicate that there were not sufficient forces acting to generate hydraulic pressure that would damage the cylinder. Therefore, the cause of the failure has not been satisfactorily determined. A new aligning cylinder was installed, and testing resumed. Subsequent tests at less-than-yield pressure were successfully conducted with no malfunctions of the aligning cylinder. However, at the discretion of VAMT, the new aligning cylinder was *not* tested under conditions that caused full compression or extension of the cylinder.

The worst load case for the canopy was concentrated loading at the center or at one end of the canopy. However, it is important to note that the strain gauges were located midway between the front and rear leg connections, which is where the maximum bending moment is for the "contact at center" and "contact at both ends" configurations, but not for the other contact configurations. An assessment of stress at full support capacity can be made by extrapolating the canopy strains shown in figure 29 to 5,338 kN (1,200 kips) of support loading utilizing a modulus of elasticity of 206,850 MPa (30×10^6 psi) for steel. The "contact at center" configuration produces a stress of 625 MPa (90,600 psi) at 5,338 kN (1,200 kips) of support capacity. Assuming a yield strength of 690 MPa (100,000 psi) for the steel, this configuration is close to producing permanent deformation in the canopy. A contact located 15.2 cm (6 in) from the canopy tip is projected to produce a stress of 393 MPa (57,000 psi) at the measured strain locations at full support capacity. However, the maximum bending moment is located farther back toward the rear leg in this loading condition, and the maximum stress is known to be greater than that measured in this test.

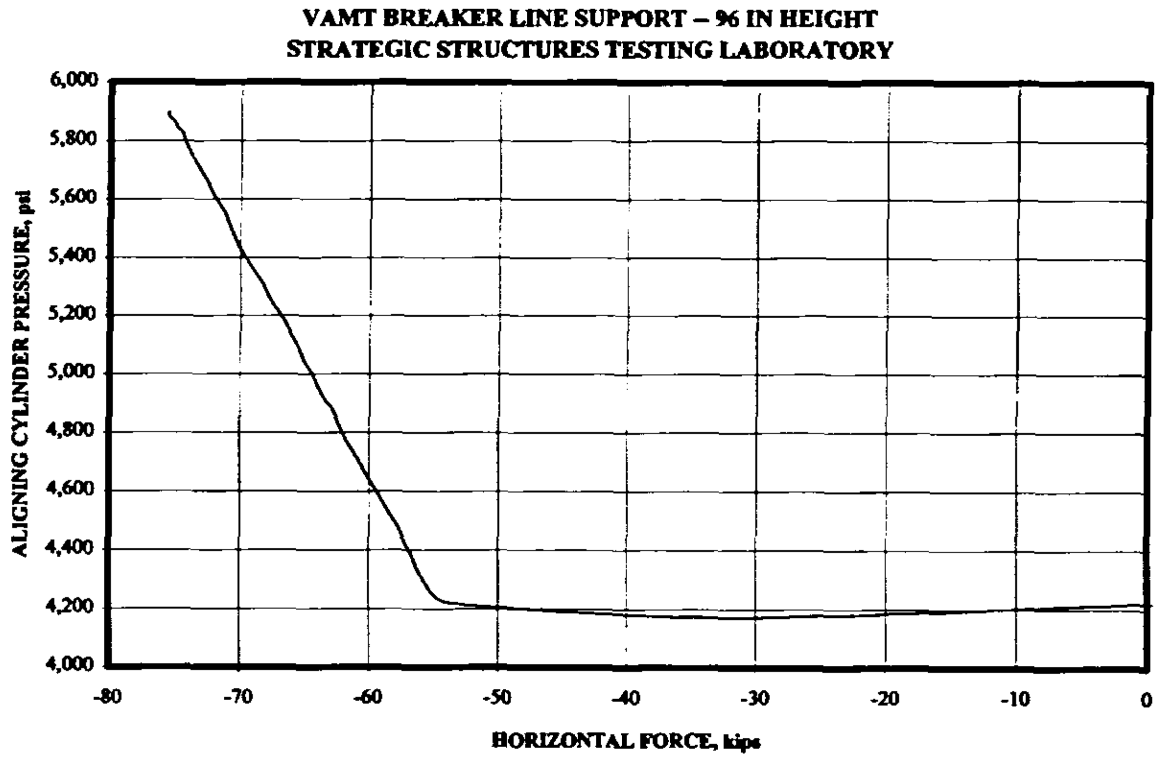


Figure 26.—Horizontal force required to initiate load development and yield pressure in the aligning cylinder.

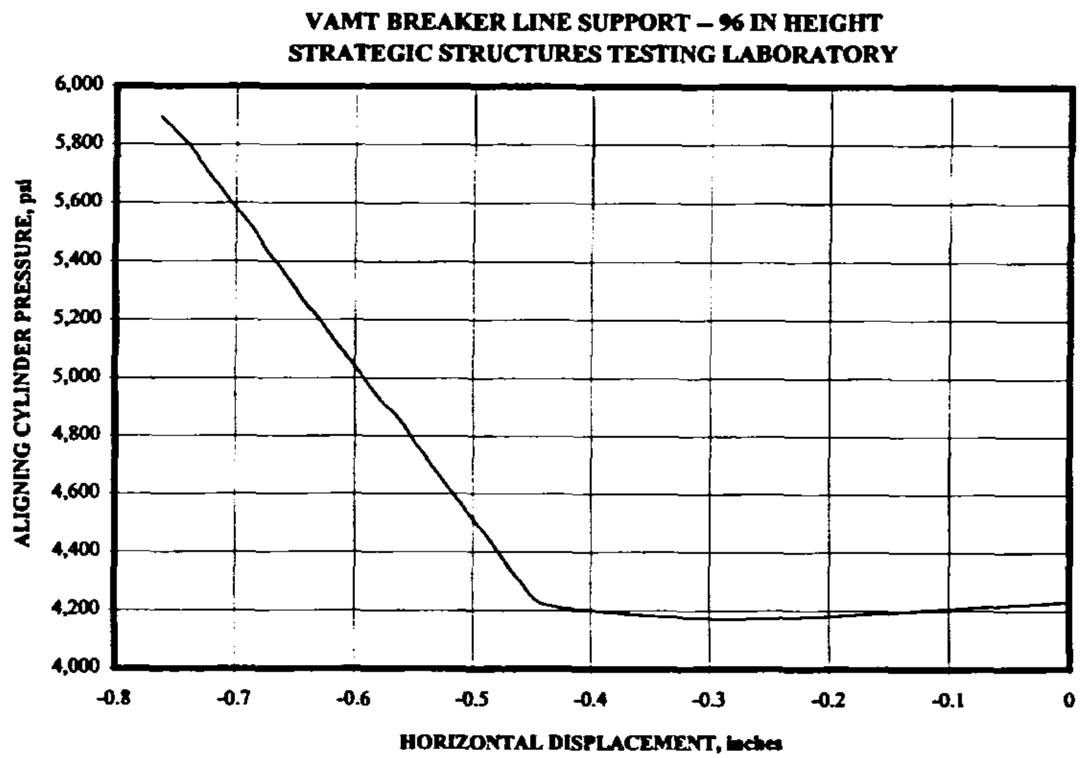


Figure 27.—Horizontal displacement required to initiate load development and yield pressure in the aligning cylinder.

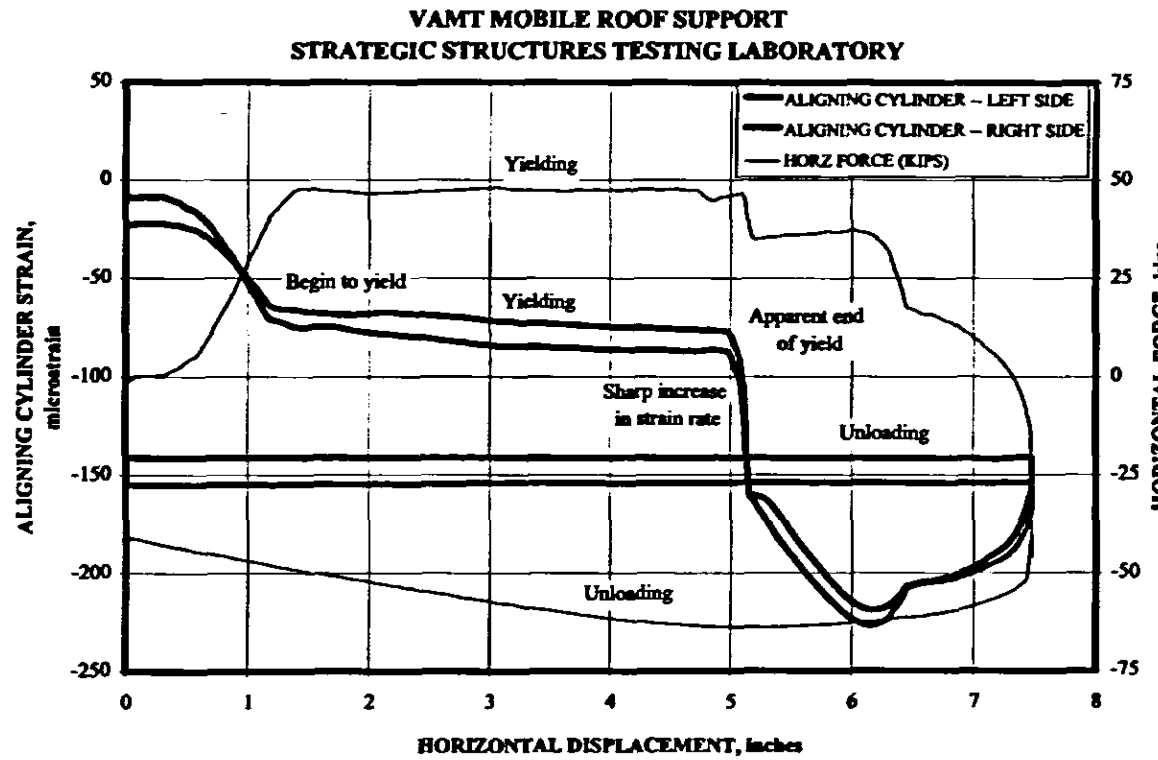


Figure 28.—Malfunction of aligning cylinder during horizontal displacement toward the plow.

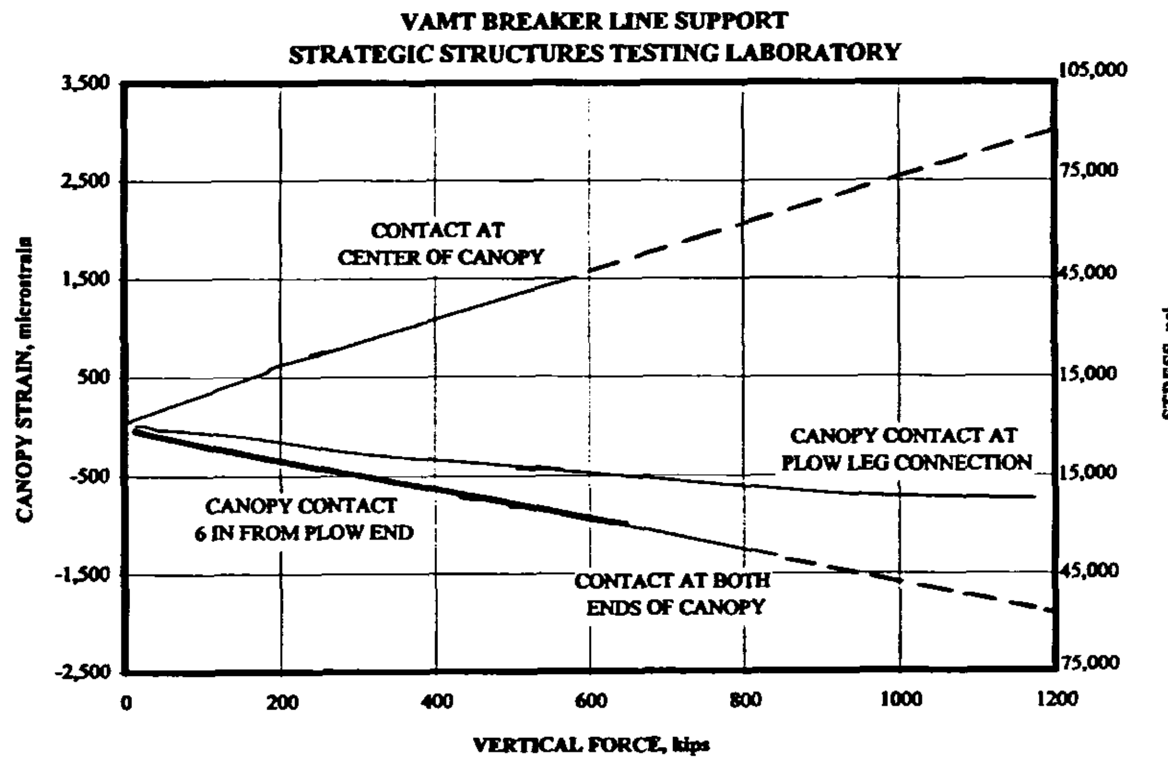


Figure 29.—Extrapolation of measured canopy strains to evaluate stress development at maximum support capacity.

Fletcher Support

The most highly stressed components in the Fletcher support were the bottom lemniscate link and sections of the base (crawler) frame. An objective of the testing was to determine loading limitations for these components. The following limitations are based on extrapolation of test data, where a margin of safety was maintained during load application. No failures of any component were observed under the test conditions.

Lateral loading of 267 kN (60 kips) produced a stress of 207 MPa (30,000 psi) in the bottom lemniscate link. Assuming a 690 MPa (100,000 psi) yield strength, extrapolation of the test data indicates that permanent deformation of the link would occur if the lateral load exceeded 556 kN (125 kips).

Horizontal loading of 400 kN (90 kips) produced stresses as high as 310 MPa (45,000 psi) in the base cross frame member at a 3.1-m (120-in) support operating height. Extrapolation of these data suggests that the maximum horizontal loading capability for the base cross frame member at the 3.1-m (120-in) operating height is approximately 934 kN (210 kips), assuming a 690-MPa (100,000-psi) yield strength. At the 3.6-m (140-in) height, horizontal loading of 445 kN (100 kips) produced stresses as high as 393 MPa (57,000 psi). Extrapolation of these data suggests that the maximum horizontal loading capability for the cross frame member at the 3.6-m (140-in) operating height is approximately 778 kN (175 kips).

This analysis is conducted for full canopy and base contact. Eccentric load conditions on the crawler frame or canopy did not dramatically increase measured component strains.

OTHER OPERATIONAL AND MAINTENANCE SAFETY CONSIDERATIONS

Any MRS will become unstable if any of the lemniscate pins fail. Since critical stresses can be developed within the range of possible horizontal and lateral loading, these pins should be periodically inspected. Additionally, before any of the lemniscate pins are removed, the canopy and lemniscate assembly should be supported to prevent both vertical and *horizontal* movement. Unrestrained movement of the canopy can result in serious injury or death.

Caution should be used when working around the support while it is pressurized. Oil leaking at these pressures can cause serious bodily damage. Likewise, pressure should be relieved before any hydraulic component is removed.

COMPARISON OF MOBILE ROOF SUPPORTS WITH TIMBER POSTS

The most obvious difference between MRS's and conventional timber posts is their size and effective roof coverage. Roof coverage depends on the manufacturer and support model, ranging from 3.3 to 7.9 m^2 (35 to 85 ft^2). In comparison, a wood post will provide less than 0.1 m^2 (1 ft^2) of roof coverage; thus, several timber posts are required to replace a single MRS.

MRS's can provide an active load of up to 4,448 kN (500 tons) to the mine roof; wood posts are strictly passive supports. The load-bearing capacity of one MRS is about the same as six 20-cm (8-in) diameter hardwood posts, as shown in figure 30. The stiffness of an MRS varies by support design and is height-dependent for a specific support. In general, an MRS operating at less than 75% of its maximum height is stiffer than a single 20-cm (8-in) diameter post with no headboard or two 20-cm (8-in) diameter posts with headboards. Figure 31 compares the stiffness of the Fletcher and VAMT supports with that of conventional timber posts and wood cribs. Comparisons with smaller diameter posts can be made by reducing the stiffness of the post in proportion to the reduction in cross-sectional area.

Another significant advantage of an MRS is that it will continue to provide close to its full rated capacity after reaching yield load and can maintain this load capacity until the full leg stroke is exhausted. Thus, whereas MRS's can provide support through a meter or more of closure, timber posts can fail at less than 2.5 cm (1 in) of convergence and have no residual strength after failure.

MRS's are also much better suited than timber posts to handle eccentric load conditions caused by horizontal and lateral roof or floor movements, gob loading, and rib rolls, which are common during pillar extraction and often kick out breaker and turn posts. In general, timber posts suffer reduced stability for anything but pure axial (vertical) loads.

CONCLUSIONS

Full-scale testing of MRS's at the Strategic Structures Testing Laboratory provided a wealth of information pertaining to their performance capabilities and limitations. The tests were conducted in the unique mine roof simulator load frame under controlled conditions that simulate in-service load conditions.

The basic design of the VAMT breaker line support and the Fletcher MRS tested in this study is similar. Design differences that impacted support performance included the lemniscate assembly, the canopy construction, and the leg cylinder design.

The VAMT support incorporated a tilt frame with hydraulic cylinders to control horizontal and lateral loading; the Fletcher support utilized rigid lemniscate links to resist horizontal and lateral loading. The tilt concept limits stress development in the support structure, but permits greater translation of the canopy relative to the base, thereby allowing greater roof movements to occur, particularly when the hydraulic tilt cylinders have yielded. The advantages and disadvantages of these designs from a ground control perspective have not been evaluated.

Differences in the leg cylinder design caused most of the differences in support performance. The Fletcher support utilized a three-stage leg cylinder; the VAMT support, a two-stage leg cylinder. Consequences of the three-stage leg design were (1) reduced support stiffness, (2) greater reductions in setting force when both the bottom *and* middle stages are fully extended, and (3) larger unrecorded roof movements, particularly when both stages are fully extended. The advantage of the three-stage leg design is greater operating range, providing a lower support profile for transporting and tramming underground.

A critical issue pertaining to the measurement of support loading and loading rate is the effect of the staging of the leg cylinders. When the bottom stage of the leg cylinders is fully extended, the dial pressure gauges do not respond to increases in support load until the setting force established in the bottom stage is overcome by pressure development in the upper stages. The unrecorded roof load is greater at high setting pressures and is minimized at low setting pressures. Operationally, the bottom stage will be fully extended when the support is first raised to a height that exceeds the bottom stage stroke and, on subsequent cycles, whenever a new maximum operating height is established. Therefore, when possible, it is recommended that the support be taken initially to a location with a height greater than the expected operating height during pillar extraction, and fully raised. This will eliminate the problem of unrecorded roof loading. However, if this practice is followed, the support should be lowered as little as possible when moving the support to the section and during cycle changes. If the support is lowered sufficiently to cause the bottom stage to fully collapse, the probability of unrecorded roof loading will increase.

Setting forces also greatly depend on leg cylinder staging and are diminished by as much as 70% for the Fletcher support with three-stage leg cylinders when the bottom and middle stages are fully extended. Setting pressure as measured by the dial gauges will not always reflect the true setting force. The same circumstances that cause unrecorded roof loading also cause diminished setting forces. It is desirable to avoid diminished setting forces because the effectiveness of the support to act as a breaker line for roof caving may be reduced for low setting forces. When comparing supports of different design, it is important to remember that the smaller diameter leg cylinder will provide less setting force for the same hydraulic pressure than supports with larger diameter leg cylinders. This is one reason that the VAMT support operates at higher pump pressure than the Fletcher support.

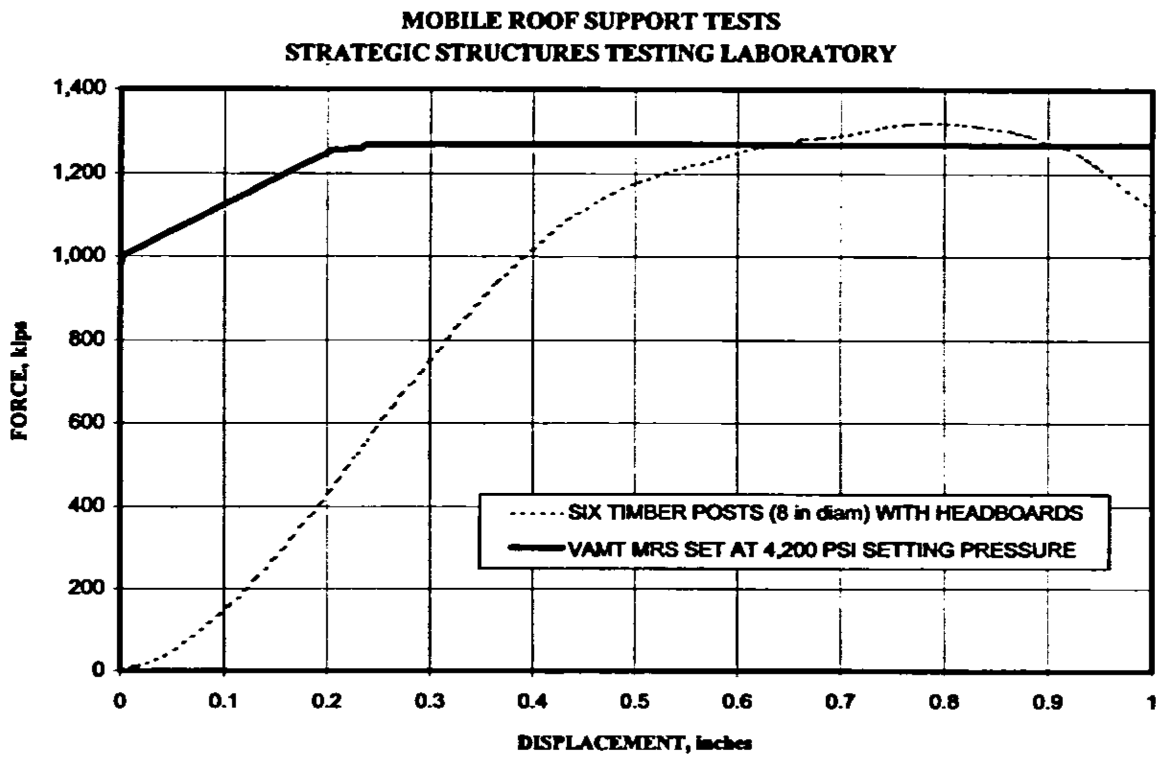
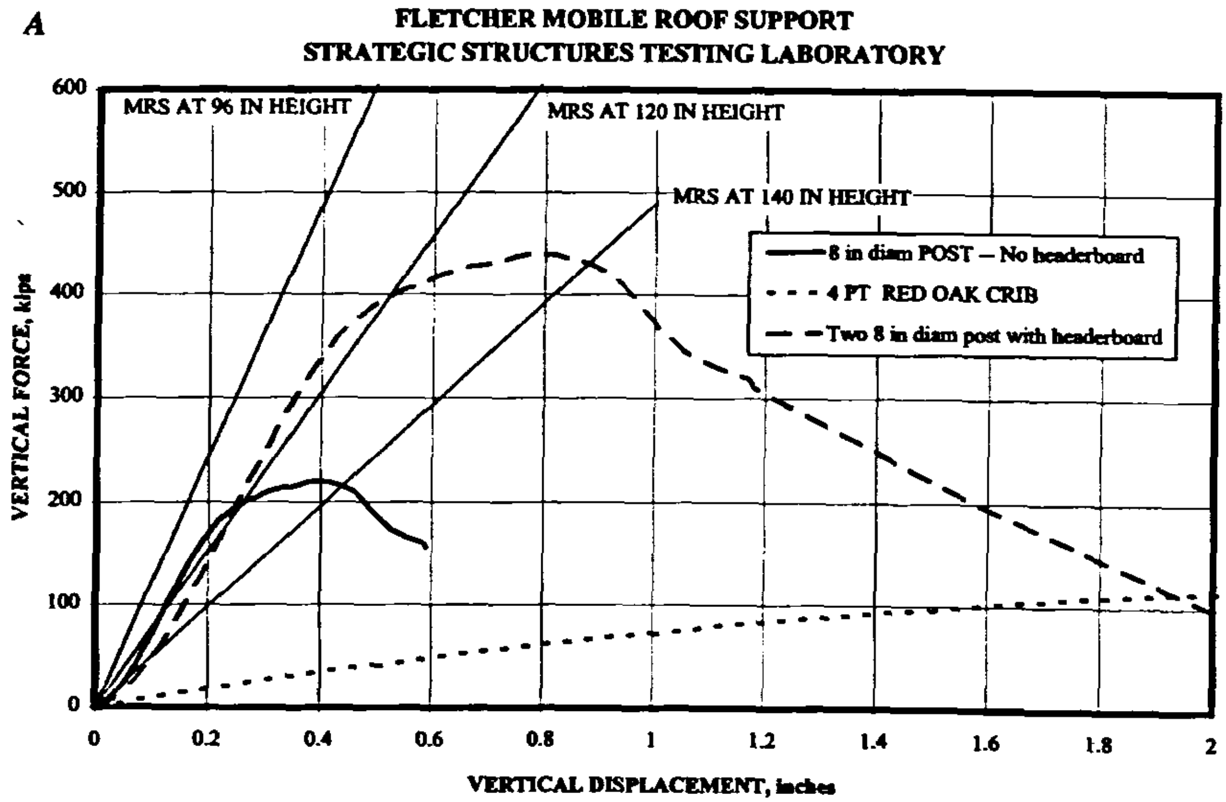


Figure 30.—One VAMT support provides about the same capacity as six high-quality timber posts.

A



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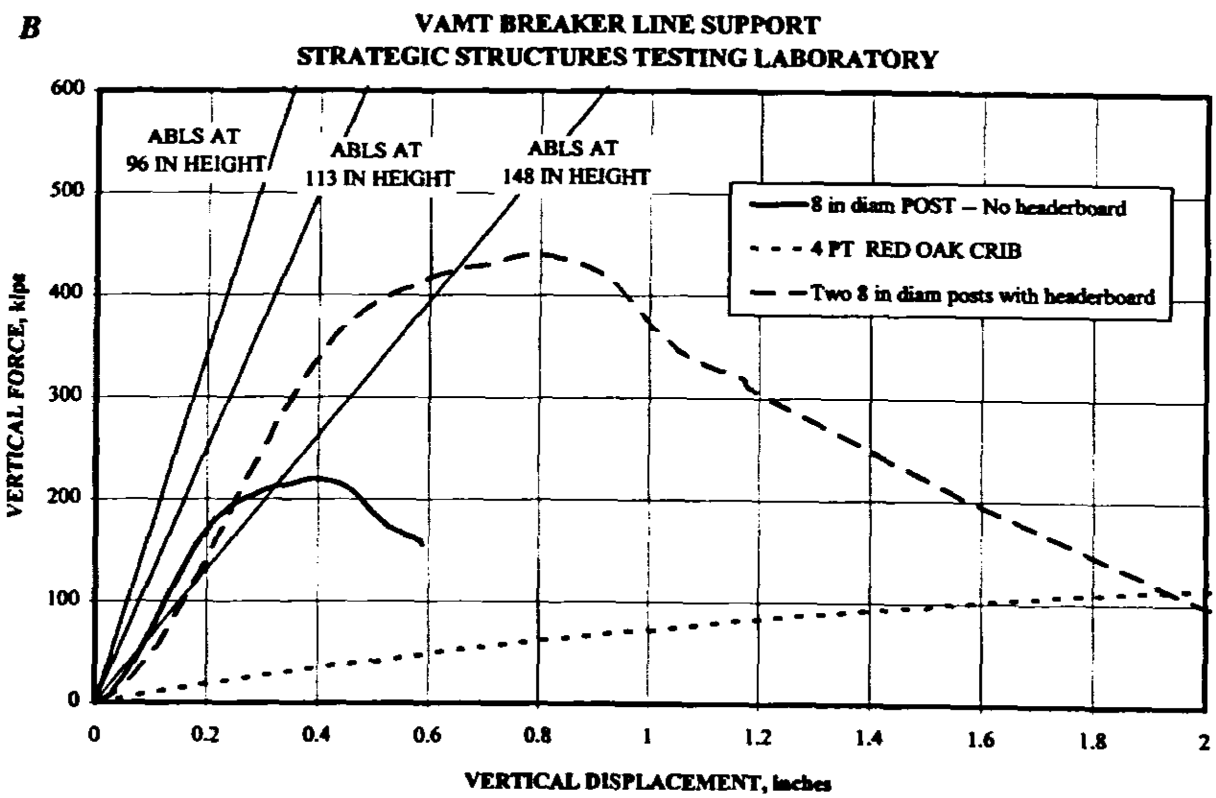

Figure 31.—Comparison of support stiffness with that of conventional timber posts. *A*, Fletcher support; *B*, VAMT support.

Both the Fletcher and VAMT supports were found to be structurally sound for *typical* load conditions. The canopy is likely to be the most highly stressed component on the VAMT support for most load conditions. Partial contact can cause stresses as high as 690 MPa (100,000 psi).

When horizontal or lateral loading is present, the lemniscate assembly and cross frame between the base crawler frames are likely to be the most highly stressed parts of the Fletcher support. Lateral loads in excess of 556 kN (125 kips) can cause damage to the bottom lemniscate link, and horizontal loads in excess of 778 kN (175 kips) can cause damage to the cross frame member. Unfortunately, there is no way to assess the magnitude of horizontal and lateral loads underground without installing additional instrumentation on the support.

The aligning cylinder on the VAMT support was damaged when it was yielded in compression by approximately 13 cm (5 in) of horizontal displacement of the canopy relative to the base. The probability of such large horizontal displacements during underground use is not known, but it is likely that this is an extreme load condition that will *not* occur during *normal* mining cycles. The cause of the failure was not satisfactorily determined. The damaged cylinder was replaced, and subsequent tests at less-than-yield pressure were conducted without any failures.

Because any support is unstable if the lemniscate link pins fail, all supports should be periodically inspected for damage or excessive deformation in the pin clevises. Furthermore, the canopy should be supported to prevent vertical and horizontal movement prior to removal or repair of an any lemniscate pin, regardless of the support manufacturer.

MRS's provide superior supporting capabilities compared with conventional timber posts. Each mobile support has a load-bearing capacity of approximately six timber posts and equivalent stiffness to two or more posts. MRS's provide significantly greater roof coverage and are much more stable for the types of eccentric loading that is common during pillar extraction. Furthermore, the active loading capability provides a more effective breaker line by minimizing initial roof movements that can lead to roof instability or caving inby the supports.

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